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EVALUATION OF REPAIR TECHNIQUES WHEN BONDING REPAIR MATERIALS TO FORTY-YEAR OLD CONCRETE SUBSTRATE

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by

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EXECUTIVE SUMMARY

Three types of surface preparation methods were tested with two different repair materials on forty-year old concrete taken from a deteriorated bridge bent. In addition, bonding agents were applied to determine if they would increase bonding strength. Mechanical hammering was used on all surfaces prior to specific surface conditioning methods combined with bonding agents so that the method could be evaluated on how well micro-cracking was removed. Failure within the substrate was categorized as the most important determination of satisfactory performance. Bond strengths, surface roughness and modulus of elasticity were also measured and used as ways to evaluate surface conditioning methods, bonding agent usefulness and repair material performance. The results of this research show that mechanical hammering without further surface conditioning results in lower bond strengths and higher percentages of failures at the repair/substrate interface. No conclusion could be made as to what surface conditioning method is ideal; high-pressure water-jetting however performed consistently. Surfaces with a scrubbed grout coating of the same material properties as the repair mix experienced the highest percentage of failures within the substrate material.

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1. Introduction

During the summer of 1999 several bridge bents from the I-15 reconstruction project in Salt Lake City, Utah were removed and saved for future research. Rowe (2001) tested several bents to their yield strength to determine if 40 years of exposure to the elements had decreased their strength. Glenn (2002) repaired some of the bents using different methods and tested those bents to determine if the repair methods increased their load capacity. One of the observations by Glenn (2002) was the failure at the interface between new concrete repair material and the substrate material of the bent. The interface is usually the weakest part of the system due to improper bonding.

The focus of this research is to determine the influence of surface conditioning methods and surface conditions on the bonding of 40-year old concrete specimens to different repair mixes. The goal of concrete repair is to achieve the same strength in the repaired/substrate system as the original monolithic system. To achieve acceptable performance proper bonding is needed between the repair mix and the substrate. Surface conditioning methods and surface conditions have a significant influence on bonding. This research will evaluate different methods and conditions and assess their performance on strengthening the repaired/substrate interface, i.e., the bonding between the repair mix and the substrate.

2. Literature review

2.1 Concrete Surface Preparation

There are two parts to concrete surface preparation: first removing deteriorated concrete and undercutting exposed reinforcing steel and second, achieving proper surface conditions so that there is proper bonding between the repair mix and “old” concrete. The manner in which deteriorated concrete is removed and how the concrete surface is prepared will often determine if a repair project will be successful (Vaysburd, 2001).

2.1.1 Removal of Deteriorated Concrete

The removal of deteriorated concrete with impacting is the most commonly used method (Vaysburd et al., 2001). Hammering with mechanical chipping hammers is the most common impact method used to remove deteriorated concrete. Hammering however has been shown to cause extensive micro-cracking which leads to failure at the repaired/substrate interface (interfacial failures) and lower bond strengths (Hindo, 1990). Concrete removal methods such as hammering may also leave the substrate surface too rough or smooth, irregular and might even close pores (Vaysburd, 2001). Hammering is not suitable for preparing the substrate surface and additional surface conditioning is required.

2.1.2 Surface Conditioning

Achieving proper surface conditions or surface conditioning is the process by which a clean, rough, sound surface is obtained, which is necessary for the repair material to bond adequately to the substrate material. Conditions encountered on surfaces that affect bonding include micro-cracking, laitance, roughness, moisture and in dry environments carbonation.

Concrete removal affects micro-cracking in the substrate. Hammering has been shown to create micro-cracking, which is a bruised layer or zone of weakness in the top layer of the substrate. Micro-cracking reduces the bond strength (Silfwerbrand et al., 1998). Holl et al., (1997) indicates that the micro-cracking zone may be .4 inch in depth. Hindo (1990) however has shown micro-cracking to extend to depths as much as .75 inches. Surface conditioning methods such as water-jetting have been shown not to create a bruised layer (Hindo, 1990).

Laitance is a thin weak layer containing cement and fines brought to the surface of the concrete by bleed water (Silfwerbrand et al., 1998). Laitance can also be caused by overworking the finish, which transports cement and fines to the surface (Holl et al., 1997). Laitance thickness may be between .06 to .12in (Holl et al., 1997). If laitance is not removed, lower bond strength and interfacial failures will occur.

The roughness of the substrate surface can also affect bond strength. Austin et al., (1995) tests resulted in higher bond strengths as roughness increased from smooth to rough. Silfwerbrand et al. (1998) concluded that a threshold exists and that beyond the threshold value roughness does not increase bond strength. According to Silfwerbrand et al. (1998) the threshold value is close to the surface roughness of sand blasted surfaces. Acceptable limits however have not yet been determined. Surface roughness may be difficult to control especially in-situ application where different machine operators and equipment are used. According to Austin et al., (1995) if there is no presence of micro-cracking and cleanliness of the substrate surface can be guaranteed, bond strength increases with roughness because of greater contact area. If the surface, however, is too rough the repair mortar may not fill all the voids creating areas of weakness (Maerz et al., 2001).

Another condition that is important is the moisture state of the substrate surface. There are however no conclusive results (Austin et al., 1995). A too dry substrate surface may absorb water from the repair mortar resulting in a porous zone. The pores in a saturated surface on the other hand will be closed and excess water will increase the water-to-cement ratio of the repair mortar consequently reducing the strength at the interface (Austin et al., 1995). Best results have been achieved with saturated surface dry (SSD) conditions (Austin et al., 1995) and SSD conditions are the industry practice. Silfwerbrand et al., (1998) recommends wetting the surface for 48 hours before applying the repair materials to achieve proper surface moisture.

Prior to application of the repair material, the surface must be cleaned. Cleanliness has the most affect on bond strength and is the most important aspect of proper surface conditioning (Silfwerbrand et al., 1998). The surface must be free of dust, oil, loose particles and other contaminants (Austin et al., 1995). Oil, grease and car fluids can penetrate deeply into the substrate requiring extensive substrate removal using mechanical methods (Holl et al., 1997). The surface needs to be cleaned after surface conditioning so that loose particles don't bond to the substrate and before repair material application to make sure the surface is clean and dust free (Silfwerbrand et al., 1998). Surface conditioning methods such as water-jetting and sand blasting are effective tools in cleaning concrete.

2.2 Material Mismatch

Cracking is typically the primary problem with repair materials and cracks usually result from a mismatch in material properties (McDonald et al., 2002). Repair materials with similar properties to that of the substrate decrease stress concentrations, which results in higher bond strengths. Modulus mismatch has been theoretically shown to affect bond performance (Austin et al., 1995). Differential shrinkage has been identified as very significant at causing cracking (McDonald et al., 2002).

Austin et al., (1995) reported that differences in modulus of elasticity could lead to stress concentrations at the bond plane, in the substrate, and in the repair material, which might reduce bond strength. McDonald et al., (2002) however, noted only a modest correlation between lower modulus of elasticity and increased in-situ performance. Performance was based on resistance to cracking because decreases in modulus of elasticity should theoretically result in lower stresses induced by shrinkage (McDonald et al., 2002).

Shrinkage will generate stress at the interface of the repair material and substrate because of restraint provided by the substrate (Austin et al., 1995). Concrete continues to shrink throughout its life so differential shrinkage between the substrate and repair material determines the effects of shrinkage. The specimens used are 40 years old and any shrinkage remaining in the substrate is minimal, increasing the probability and effects of differential shrinkage. McDonald et al., (2002) performed unrestrained and restrained shrinkage tests to determine the affects of shrinkage on the performance of a variety of repair materials and their resistance to cracking. Their research showed that as unrestrained shrinkage decreased cracking decreased (McDonald et al., 2002). Restrained shrinkage tests correlated significantly with unrestrained shrinkage tests providing conclusive results on the importance of limiting shrinkage to offset problems from cracking.

2.3 Bonding Agents

There are advantages and disadvantages of using bonding agents in concrete repair. Bonding agents can be used for a number of reasons: as a way to wet the surface improving contact and spreading of the repair material; as a way to fill small pockets that a stiffer mortar could not penetrate improving contact area; and as a way to increase adhesion (Austin et al., 1995). If grout is used as a bonding agent, the grout may assimilate loose particles on insufficient cleaned surfaces (Silfwerbrand et al., 1998).

There are negative aspects or risks when using bonding agents. If the bonding agent dries out prior to placement of the repair material then it becomes a bond breaker (Austin et al., 1995). If epoxy is a bond agent, its performance may be affected by how it is stored, handled, applied and cured (Maerz, 2001). Grouts often have a high water-to-cement ratio, which reduces strength and introduces the risk of cohesive failure within the grout itself (Silfwerbrand et al., 1998). A chemical binder will lead to two interfaces, which increases the amount of possible planes of weakness (Silfwerbrand et al., 1998). Li et al., (2001) however noticed from SEM that there was only one interface between repair and substrate materials with a binder when specimens were placed on a vibrating table during application of the binder.

2.4 Concrete Finishing

Upon placement of the repair material, finishing and curing can also affect bond performance. Adequate compaction of the repair material is necessary for proper finishing. Compaction allows for a dense repair material and is necessary so that air pockets do not form at the interface of a rough surface (Silfwerbrand et al., 1998). Silfwerbrand et al. (1998) noted air pockets in cores on waterjetted surfaces.

Curing reduces the risk of cracking due to differential shrinkage (Silfwerbrand et al., 1998). Curing leads to higher strengths, improved durability and reduction of plastic cracking (Silfwerbrand et al., 1998). Curing should begin immediately after finishing of the repair mix and shall last a minimum of five days (Silfwerbrand et al., 1998).

3. Procedures

The specimens for this research were taken from bent 15N (Rowe, 2001 and Glenn, 2002). Portions of bent 15N that were undamaged from prior testing were selected for specimen removal. Figure 3.1 shows bent 15N after testing by Glenn (2002) and the locations where the specimens were taken. A total of six specimens (slabs), 12 inches thick were cut with a diamond studded wire saw (Figure 3.2). The outermost edge of the cantilever portion was also used since it had no signs of damage. The seventh slab is the base area of bent 15N that had been cut earlier with a diamond saw to allow the bent to fit in the testing apparatus (Glenn, 2002). One of the slabs is shown in Figure 3.3. The slabs cut from the region that was undamaged during testing are labeled in Table 3.1 with corresponding surface preparation methods. Slab 15NB is from the base of the bent and slab 15NE from the end of the cantilever. The other slabs, 15N1 through 15N5, are labeled in order from the outermost slab to the innermost slab (Figure 3.1).

Upon the removal of the specimens by diamond cutting, hammering was carried out to mimic the effects of removing deteriorated concrete as done in field application. Hammering was also necessary to roughen the surface to obtain a more realistic profile that would be encountered in-situ. A 15 pound mechanical hammer with a bush bit was used to roughen the surface as well as introduce micro-cracking so that additional surface preparation method effectiveness could be evaluated (Figure 3.4). The bush bit was recommended by a concrete repair specialist (Mullen, 2003) as a way to introduce most effectively and quickly micro-cracking as well as roughens the surface profile. The difference in surface roughness between a wire cut slab and hammering is shown in Figure 3.5.

After all slab surfaces were hammered, surface conditions were achieved through several methods. These methods remove micro-cracking and laitance and adequately roughen the surface. Finally the substrate surface is cleaned and proper surface moisture condition is achieved. Four types of surface conditioning methods were used: mechanical hammering, high-pressure water-jetting, sand blasting and shot blasting.

Slab 15NE did not receive further surface conditioning after it had been hammered. This was carried out to determine the effectiveness of only hammering as a surface conditioning method and to have a baseline.

Water-jetting can be used to remove deteriorated concrete as well as a surface conditioning method. Water-jetting leaves the surface rough, doesn't cause micro-cracking, cleans it free of dirt and contaminants, and leaves a sound substrate (Silfwerbrand et al., 1998). In addition water-jetting doesn't damage reinforcing steel and cleans it free of rust. HydroChem Industrial Services, Inc. of Draper, Utah conducted the water-jetting. Slab 15N4 as seen in Figure 3.6 was jetted at a pressure of 40ksi on both faces while 15N5 as seen in Figure 3.7 was jetted at a pressure of 20ksi on both faces. HydroChem used 40ksi and 20ksi to mimic industry practice. Figure 3.8 shows the .018 in 3-jet revolving nozzle used during jetting. The nozzle has a capacity of 4.41gpm. HydroChem used the Gyro Gun shown in use in Figure 3.9. Appendix A contains a data sheet of specifications and uses of the Gyro Gun.

Sand blasting is a surface conditioning method. Sand blasting or abrasive blasting is the most common used method by the industry to clean concrete surfaces and reinforcing steel (Vaysburd et al., 2001). Sand blasting produces a textured, physically sound surface substrate free of contaminants and fines (Holl et al., 1997). Two abrasive diameter (mesh) sizes were used for sand blasting. A low free silica mineral abrasive mesh size 8-20 from Best Grit of Anaconda, Montana, shown in Figure 3.10, as well as a 60 mesh Ruby Garnet product, shown in Figure 3.11 (Appendix A contains a data sheet on Ruby Garnet) were used for sand blasting. The 8-20 mesh was chosen for heavy cleaning and the 60 mesh was chosen for light cleaning. Figures 3.12 and 3.13 show slabs 15NB and 15N1 after sand blasting had taken place. Figure 3.14 shows the nozzle and machine used. The operator of the sand blasting machine used prior experience as a judgment for time of exposure.

Shot blasting is also a surface conditioning method. Shot blasting is the method most commonly recommended by coatings manufacturers (Holl et al., 1997). Shot blasting is very effective at cleaning, removing hardened films of contamination and texturing concrete surfaces (Holl et al., 1997). Shot blasting is dust free because it is self-containing. The disadvantage of shot blasting is that it can only be used on horizontal surfaces and is only suitable for large unobstructed surfaces (Holl et al., 1997). There were two sizes of steel shot chosen for shot blasting surface preparation; 230 grain (.6mm or .0236in), the smallest shot size for the machine and 330 grain (.8mm or .0315in), the largest shot diameter for the machine. Both steel shots sizes are Ervin Industries Amasteel products. The data sheet on the steel shots and SAE specifications are presented in Appendix A. Figures 3.15 and 3.16 show slabs 15N2 and 15N3 and the effects of respective shot blasting after hammering. The shot is shown in Figure 3.17 and the Blastrac 1-8DEC machine is shown in Figure 3.18. A data sheet on the equipment is presented in Appendix A. The machine operator used prior experience as a judgment for time of exposure.

After the slabs were conditioned, they were cleansed with low pressurized water, roughness tests were conducted and surface moisture requirements obtained. Substrate surfaces were washed with low pressurized water as recommended by Silfwerbrand et al., (1998). The machine used was a 4000psi sprayer. The washing was carried out carefully since water pressurized to similar pressure has been used as a surface conditioning method (Wells et al., 1999). To avoid any additional surface conditioning that might have resulted from washing; the sprayer nozzle was held at a distance of approximately 2ft from the surface since the goal of this procedure was only to clean the surface of dust and loose particles (Figure 3.19).

Roughness tests were performed in accordance to ASTM E 965 – 96. Glass bead size satisfying requirement 6.1.1 of ASTM E 965 – 96 was used and the beads were placed in a beaker to a volume of about 30ml. On the PCC side the standard weight of the beads was 44.6g while on the SSRP side the weight was 44.0g because of a simple mathematical error by the author. The error was discovered after the entire research was conducted and only has a minor affect when comparing the roughness of slabs with PCC against SSRP repair materials. The basic layout for roughness testing is shown in Figure 3.20. Figure 3.21 shows the instruments used including the hockey puck used for spreading the beads. Figure 3.22 shows the order and orientation in which diameter measurements were taken.

The slabs were pre-wetted for 48 hours using burlap sacks (Figure 3.23) prior to application of the repair material. Upon removing the burlap the substrate surface was again cleaned with low pressurized water to remove any dust or dirt left from the burlap sacks. Prior to applying bonding agents and repair materials, SSD conditions were achieved (Figure 3.24).

4. Repair materials

Two types of mixes were used in this research: high performance Portland Cement Concrete mix (PCC) and SikaSet Roadway Patch 2000 (SSRP). The goal was to obtain a low shrinkage repair mix that has a similar modulus of elasticity to that of the substrate. Each repair mix was approximately 2 inches thick when applied to the substrate. Table 4.1 presents a summary of compressive strength and modulus of elasticity for all repair materials and substrate. Table B.1 in Appendix B presents the compressive strengths and modulus for six cored cylinders taken from the substrate material of 15NB. The cores were obtained and tested in accordance with ASTM C 42/C 42M - 99.

4.1 Portland Cement Concrete Repair Material

The mix specifications for the PCC repair material are shown in Table 4.2. Appendix A presents the product descriptions for the Portland cement, water reducer, air-entrainment and sand, respectively. Restruction Corp., which assisted the author during this research, has used similar proportions with success throughout Utah and Colorado (Collins, 2003). The mix is a relatively low shrinkage mix and has met bond strength requirements when used as a repair material. To control shrinkage, Collins (2003) suggested a ¾ in aggregate. The ¾in aggregate, however resulted in a mix that was difficult to place around the reinforcing bars, therefore, pea gravel was used. The consequence of such smaller size aggregate was not determined.

Measuring, mixing and application of the repair mix were done by experienced workers from Restruction Corp. in the Structures laboratory at Brigham Young University under the supervision of the author. First, half of the water was mixed with the air entraining and water reducer admixtures. The rest of the contents were added followed by the last half of the water. A total of three mixes were made to fill the forms. No cylinders were taken at the time but an additional mix was made, with half the proportions as done during actual repair, to obtain six cylinders for compressive testing. Table B.2 lists the compressive strength and modulus of elasticity of six cylinders at 28-day strength for the PCC repair material. Figure 4.1 shows the PCC repair material being applied to the substrate. Figure 4.2 shows a finished surface of PCC repair material.

4.2 SikaSet Roadway Patch 2000 Repair Material

Collins (2003) recommended the use of SSRP. Appendix A presents specifications for SSRP. Restruction Corp. is currently conducting bridge repair work for the Utah Department of Transportation (UDOT) which is currently specifying SSRP mix, so using the mix on this research program was very realistic. In addition to each 50-lb bag of SSRP, 25 pounds of No. 8 pea gravel was added as instructed by the SSRP data sheet because the depth was greater than 1.0 inch and to help prevent high shrinkage.

SSRP is a very rapid hardening highway-patching material that can be used for highway overlays, full depth patch repairs and as a structural repair material for bridges, dams, parking structures and ramps. When applied as an overlay SSRP can withstand vehicle traffic after just 2hrs. Table B.3 of Appendix B lists the compressive strength and modulus of elasticity for SSRP at 16 days and Table B.4 of Appendix B lists those properties at 28 days. Figure 4.3 shows the SSRP repair material being applied and Figure 4.4 shows finished SSRP repair material.

4.3 Bonding Agents

Two types of bonding agents were used: a three-part epoxy and grout. In addition some specimens were obtained from areas where no bonding agent or grout was applied. Figure 4.5 shows the typical layout for the bonding coats before the repair material was applied. SSD conditions were maintained when applying the bonding coats and when applying the repair material. In dry environments like Utah, the substrate surface does not stay wet for too long. Figure 4.6 shows one of the workers for Restruction Corp. applying water to the substrate to keep SSD conditions.

The three-part epoxy was Sika Armatec 110 EpoCem and was recommended by Collins (2003). The specifications are presented in Appendix A. The epoxy is a dual use three-part epoxy that can act as an anti-corrosion coating for reinforcing steel or as a bonding agent when placing repair mortar to existing hardened concrete. The specifications mention that the epoxy can sit for up to 24 hours in 40F heat or a minimum of 6 hours when the temperature is 95F. At 68F the epoxy can sit for 12 hours. The Sika representative suggested however that the epoxy should not sit longer than six hours without repair material being applied at that temperature. After the epoxy had been mixed and applied there was a maximum sitting time of two hours before the PCC mix was applied. During the application of SSRP mix the epoxy sat for about 45 minutes before the repair mix was applied. Figure 4.7 shows how the epoxy was mixed. Figure 4.8 shows how the epoxy was typically scrubbed into the substrate.

The PCC grout was a mix of Portland cement and water with a "brusheable" consistency; exact proportions are unknown and the consistency was similar to that used by experienced workers from Restruction Corp. The grout sat about 20-30 minutes before the PCC mix was placed. Figure 4.9 shows the grout being mixed and Figure 4.10 shows the grout being scrubbed onto the substrate.

The SSRP grout was SSRP repair mix scrubbed into the substrate. This procedure is the most common method used by Restruction Corp. and has many advantages: eliminates any difference in strength or modulus of elasticity between the bonding agent and repair/substrate system; assimilates loose particles on insufficient cleaned surfaces; and fills any voids left by rough surfaces, which is paramount with a rapid set, stiff mix product like SSRP. Figure 4.11 shows the SSRP grout being scrubbed onto the substrate.

Proper compaction and curing is essential to adequate performance. Compaction was accomplished with hand trowels shown in Figure 4.12. This procedure was necessary because of the shallowness of the repair overlay and the minimal amounts of repairable material. Figure 4.13 shows specimens after repair material application being cured. The specimens were cured for seven days at approximately 70 degrees F with burlap and a plastic covering.

5. Testing

There is no protocol or standardized testing procedures for testing of the specimens. Austin et al., (1999) suggests conducting multiple types of tests to evaluate the interface under various stress conditions so that a bond failure envelope can be constructed. Such procedure covers the full range of stress combinations that a repaired structure actually experiences thus giving a clearer indication of bond. Repaired interfaces that are subject to direct tension have the greatest dependence on the bond while repaired interfaces subject to direct shear depend on the bond as well as aggregate interlock which adds greatly to bond capacity (Vaysburd et al., 2001). The objective of this research is to determine the bond performance. Therefore direct tension testing will subject the weakest part of the repairer/substrate system the repaired/substrate interface to stresses that will cause failure at the minimum strength of the repaired/substrate interface.

The direct tensile test (or pull-out test) was used because of four important aspects: allows for in-situ testing, is sensitive to surface conditions, allows for a direct tensile stress to be applied across the interface, and allows for identification of the failure mode. Hindo (1997) has shown that the direct tensile tests provide consistent and reliable results for in-situ bond strengths. In-situ testing is important because the method of placing and curing concrete surface conditions of the substrate and environmental factors have a great influence on the quality on bonding (Ali et al., 1998). Bungey et al., (1992) and Austin et al., (1995) provide an in depth discussion on direct tensile testing.

A 2.75-inch diameter partial core was drilled through the repair mortar into the substrate. The coring rig is shown in Figure 5.1. A typical layout of core locations is shown in Figure 5.2. As determined by Bungey et al., (1992) and Austin et al., (1995) shallow cuts into the substrate result in stress conditions that underestimate bond strength. The European standard (Austin et al., 1995) suggests 15 ±5 mm (.59 ±.20 inch) while Bungey et al., (1992) suggests a minimum of .787 inch. For this research 1 inch was used.

Steel disks were glued onto a clean, sanded core with epoxy and the pullout device was attached and the test performed. Bungey et al., (1992) recommend minimum disk widths and diameters but the device used in this testing program was slightly different and therefore there was no baseline.

Close observation of the specimen revealed that because of bleed water and laitance the surface of the repair material was very weak. After cores were drilled, their tops were grinded down to reach sound repair material as shown in Figure 5.3. Such a procedure prevented failure at the surface layer of the repair material.

The custom testing device shown in Figure 5.4 was used in this testing program (Collins 2003). This device is a manual operated jack with load readouts in 20lb increments (up to a 2000lb maximum). The dial is shown in Figure 5.5. Figure 5.6 shows the chain link system that was attached from the jack to a bit that screws into the hollow steel caps shown in Figure 5.7. These caps were glued onto thoroughly cleaned cores. Figure 5.8 shows a two-part epoxy being applied to the cores. Epoxy was also applied to the base of the steel cap and then was pressed onto the core as shown in Figure 5.9. Figure 5.4 shows the orange steel arm that was placed in the jack and slowly pushed down raising the jack that in turn raises the steel disk applying a tension load over the surface area of the core. The complete set-up is shown in Figure 5.10.

Loading rates are suggested by the European standard (Austin et al., 1995) and by various researchers so that test results can be compared. Although loading rates are suggested, testing devices, loading controls and data acquisition systems vary tremendously making almost impossible any comparison. Such was the case in this research. The loading rate of the testing device for this research could not be controlled accurately and consistently. Although higher loading rates will generally result in higher failure loads, there is no correlation about loading rates and bond strength testing (Austin et al., 1995). The authors could not find direct tensile testing devices in the United States where the rate of loading could be controlled. Care was taken in minimizing eccentricity as noted by Austin et al., (1995).

6. Procedural observations

6.1 Specimens

The surface of the slab cut from the bridge bent and used as specimens was not the surface exposed to environmental conditions. Thus the initial conditions of the specimens can be assumed to be in better condition than the outer exposed surface areas. Even though this was the case, during repair all deteriorated substrate material would have been removed so that the repair material had a sound substrate to bond. Thus the final condition of the specimen just prior to application of the repair material is similar to that of what would be encountered in an actual bridge repair situation.

How deep deterioration has affected the bridge bent over its life is not known. The concern is even though the substrate surface that was repaired received surface preparation because of its prior vertical orientation drilling close to the edge could have occurred into deteriorated substrate. Therefore the drilled core specimens were drilled far enough from the exposed surfaces to minimize this affect.

The bridge bents were constructed vertical so there might be an uneven vertical distribution of aggregate. It is not known if larger aggregate sank to the bottom and the finer aggregate stayed at the top. Because the testing occurs along the vertical plane this possible uneven distribution of aggregate might have an effect on results of this testing program.

Many truckloads of concrete were needed to cast the bridge bents. The slight difference in concrete strength of each truck load, casting conditions, and time between each load may also have had an affect on the results of this testing program. Finally the quality of workmanship as far as compacting and curing may also have had an affect on the results of this testing program.

Even though these conditions may have had an effect on the results of this testing program, the author believes the conditions encountered during this research project are similar to those encountered in an actual bridge repair situation.

6.2 Effects of Surface Conditioning

The surface profile on two faces of two slabs, 15NB and 15N1 were already rough before hammering. The surface profile of these two faces is much more likely to be encountered in the field than what was prepared by hammering the smooth sawn surfaces. The surface profiles of these two faces (Figures 6.1 and 6.2) were a lot rougher when compared to typical surfaces after hammering with the bush bit. The extremely rough surface on 15NB resulted in a repair material depth of 4 inches so that there was enough height to maintain a minimum 2in thickness in the repair material. The area outside of the box shown on Figure 6.1 was the area where the specimens were obtained. A few specimens were obtained from within the box area to compare results. The extremely rough area on 15N1, on the left side of Figure 6.2, was avoided and the flatter area was used to obtain the specimen.

The 40ksi pressure used was very intense and easily removed any weak concrete. When the substrate was exposed too long to this extreme pressure, the aggregate was completely exposed and the cement paste around the aggregate was completely removed. Such a procedure resulted in an extremely rough surface (Figure 6.3). The author tried to then remove this extremely rough surface but could not with the equipment at hand. The author decided therefore to expose the substrate for a shorter time to water-jetting to avoid this problem. Because water-jetting at high pressures can potentially cause micro-cracking, although insignificant when compared to hammering, the author believes that if the substrate was exposed for too long significant micro-cracks might have developed. The substrate was exposed long enough to remove unsound substrate, laitance, micro-cracks, thoroughly clean and leave the substrate with a rough profile consistent with the experience of the operators.

No standard of time of exposure to water-jetting was used for either pressure. It was left to the judgment of the operator. The operator looked for adequate aggregate exposure and a diminished rate of concrete removal indicating that any laitance, unsound substrate or areas of weakness were removed. Firmly bonded aggregate was left intact while loosely bonded aggregate was removed. Water-jetting did not remove rust or corrosion from exposed rebar. The surface however was thoroughly cleaned and the effects of the water jetting easily noticed. The difference in surface roughness and aggregate exposure between the two pressures was also very noticeable.

It was very difficult to visually determine the effects of shot and sand blasting on the roughened surfaces. Clearly shot blasting was removing concrete because of the dust in the vacuum attachment shown in Figure 6.4 as well as a noticeable removal of surface dust and dirt as shown in Figure 6.5. Removal of corrosion on the exposed reinforcement bars was also noticeable (Figure 6.6) and the removal of spray paint (Figure 6.7). Shot blasting was done on a patch of pavement and the effects are shown in Figure 6.8. The pavement was only exposed for a short time and a lot of it was removed. The affects of shot and sand blasting could be felt by touching. The softer the surface the more susceptible it is to shot and sand blasting effects. Abrasive blasting made the pre-hammered surface profile rougher and increased the frequency of peaks and valleys (Figure 6.9). It did not expose however the aggregate as water-jetting but it did roughen the surface of the aggregate.

Both sand and shot blasting did not remove considerable amount of concrete and would be very inefficient at chipping or removing substantial amount of concrete. Hammering has to be used in conjunction with shot and sand blasting. The surface is thoroughly cleaned by both methods. It is, however not apparent that the problems of laitance and micro-cracking are removed with sand and shot blasting. The large size of aggregate, the amount of aggregate and the age of the substrate might have had an affect on the effectiveness of shot and sand blasting.

7. Measured Results

7.1 Performance Criteria

Bond performance can be measured by either bond strength or where the failure occurs. The goal of doing repair work is to avoid failure at the interface and to meet minimum failure loads, thus if a correlation exists between these two criteria then requiring both strength and location performance would be the best option. If a correlation does not exist then one has to determine which is more important. Assuming that minimum bond strength requirements are met, the only way to properly evaluate surface conditioning methods is to determine the mode of failure. If the failure occurs at the interface, then preparation techniques have failed and the repair/substrate system has not acted monolithically. If the failure occurs within the substrate, then surface conditioning methods have worked at developing a monolithic system and the potentially weakest part of the system has succeeded at being stronger than either the substrate or repair materials. For this reason, assuming that bond strengths are greater than minimum requirements and that there is no correlation between bond strength and mode of failure, the mode of failure will be considered more important and used as a measure for success.

ACI committee 503 (Hindo, 1990) stated that bond strength of 100psi is adequate for repairs while CSA A23.1 (Wells, 1999) set the minimum standard at 130psi. A stress of 130psi was set as the minimum standard for the reason that it is a more astringent requirement. As long as the minimum bond strength is satisfied then surface conditions and preparation techniques are valid. If the failure occurs within the repair mix or substrate materials then the measured strength is minimum bond strength of the interface. Cores were pulled and examined to determine the mode of failure, which were classified as follows: repair, repair/interface, interface, substrate/interface and substrate.

Failure within the repair material as shown in Figure 7.1 constitutes too weak of a repair material. Failure within the repair/interface as shown in Figure 7.2 indicates a lack of proper compaction or adhesion between the repair material and the bonding agent. Failure at the interface as shown in Figure 7.3 can be considered a complete failure of the system because proper adhesion did not take place, bonding agents were not efficient and surface conditions could have been unsound due to a lack of proper surface conditioning techniques. Failure within the substrate/interface as shown in Figure 7.4 is indicative of micro-cracking and is a typical result. If the substrate was properly cleaned and the repair mix properly mixed, laid and cured then failure close to the interface that lies within the substrate is an indication of poor surface conditioning methods, mainly too much mechanical damage that causes micro-cracking (Austin et al., 1995). Because the goal of concrete repair is to achieve a sound bond and strength similar to a monolithic system, failure deep within the substrate as shown in Figure 7.5 is indicative of success.

Tables 7.2 through 7.4 contain summary of results for PCC, SSRP 16-day and SSRP 28-day repairs, respectively. The results shown are averages of bond strength and modes of failure noted during actual testing. Individual test results are presented in Appendix B, Tables B.5 through B.7. Figures 7.6 through 7.8 are correlation plots between percent substrate failure and bond strength for PCC 34-day, SSRP 16-day and 28-day repairs, respectively. There is no correlation between the rate of substrate failures and bond strength for the PCC, for SSRP at 16 days, and for SSRP at 28 days.

7.2 Surface Conditioning

Surface conditioning involves removal of surface contaminants and micro-cracking and sufficiently roughening the surface. The effects of substrate roughness as produced by surface conditioning methods will be presented followed by individual surface conditioning method results. Surface conditioning method results are reported in Tables 7.5 through 7.7. These Tables present averages of each surface conditioning method over all bonding agents according to repair material type.

7.2.1 Surface Roughness

Table 7.8 contains a summary of roughness results from the PCC side. Individual results are presented in Table B.8 in Appendix B per ASTM E 965 - 96. Hammering produced the least rough surface with a mean textured depth (mtd) of .043 inch while water-jetting at 40ksi produced the roughest surface with a .096 inch mtd. The difference in mtd values between hammering and abrasive blasting is only .01 inch while water-jetting resulted in dramatic increases in mtd. Figure 7.9 shows roughness from surface conditioning methods on the PCC side against rate of substrate failures. Figure 7.10 shows roughness from surface conditioning methods on the PCC side against rate of substrate/interface failures. Figure 7.11 shows roughness from surface conditioning methods on the PCC side against bond strength.

Table 7.9 lists roughness results from surface conditioning methods for the SSRP side. Individual results are presented in Table B.9 in Appendix B per ASTM E 965 - 96. Data from both sand blasted slabs are missing because those surfaces had voids greater than 1 inch. There is no standard to measure roughness for surfaces with voids greater than 1 inch. Just as the PCC side, hammering was the least rough and the 40ksi water-jetted side the most rough with mtd values of .041 inch and .070 inch, respectively. Shot blasting had an mtd only slightly higher than hammering while water-jetting was considerably different. Figure 7.12 shows roughness from surface conditioning methods for SSRP at 28 days against rate of substrate failures. Figure 7.13 shows roughness from surface conditioning methods for SSRP at 28 days against rate of substrate/interface failures. Figure 7.14 shows roughness from surface conditioning methods for SSRP at 28 days against bond strength.

7.2.2 Surface Conditioning Methods

Figures 7.15 through 7.17 show correlation between percentage substrate failure and bond strength for PCC, SSRP 16-day and SSRP 28-day repair, respectively. Figures 7.18 through 7.20 show correlation between percentage substrate/interface failure and bond strength for PCC, SSRP 16-day and SSRP 28-day repair, respectively. Refer to Tables 7.5 through 7.7 for a summary of results of surface conditioning methods.

Hammering produced failures of all specimens at the interface for both PCC and SSRP. When PCC was used 100% of the failures were substrate/interface and with SSRP, 67% of the failures were substrate/interface. Hammering with PCC resulted in the lowest average bond strength of 149psi while the bond strength was 190psi for hammering with SSRP.

Sand blasting with 8-20 mesh produced good results with both repair mixes. Substrate failure rates were 25%, 80% and 88% for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Substrate/interface failure rates were 75%, 0%, and 13% for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Relatively, however sand blasting resulted in low bond strengths: second lowest for PCC, lowest for SSRP 16-day and second lowest for SSRP 28-day repair.

Sand blasting with 60 mesh produced 6%, 25%, and 100% rates of substrate failures for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Substrate/interface failure rates were 83%, 50% and 0% for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Sand blasting with 60 mesh on the PCC side produced average bond strength at 235psi but produced the highest bond strength for SSRP 16-day and 28-day tests, 263psi and 288psi, respectively.

Shot blasting with 230 steel performed the best for PCC repair with substrate failure rate of 42%, substrate/interface failure rate of 58% but had a lower than average bond strength at 225psi. At 16 and 28 days with SSRP repair material substrate failure rates were 38% and 67% while substrate/interface failure rates were 0% and 17%, respectively. At 16 days the average bond strength was 195psi and at 28 days was 167psi, which is below average.

Shot blasting with 330 steel produced substrate failure rates of 20%, 50%, and 29% for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Shot blasting with 330 steel had consistently high substrate/interface failure rates at 73% for PCC repair and 50% and 71% rates for SSRP repairs at 16 days and 28 days, respectively. Shot blasting with 330 steel produced average bond strengths of 237psi for PCC, 211psi and 212psi for SSRP 16-day and 28-day, respectively.

Water-jetting at 40ksi produced good results with PCC but very poor results with SSRP repair at 16 and 28 day. Water-jetting at 40ksi with PCC repair produced the second best results with substrate failure rate of 38%, substrate/interface failure rate of 15% and the highest average bond strength at 257psi.Waterjetting at 40ksi resulted in 100% interfacial failures in the SSRP at 16 days and at 28 days and lower than average bond strengths of 165psi and 194psi, respectively.

Water-jetting at 20ksi repair produced substrate failure rates at 13%, 75%, and 71% for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Substrate/interface failure rates were 38%, 0%, and 29% for PCC, SSRP at 16 days and SSRP at 28 days, respectively. Bond strengths were 237psi, 213psi, and 234psi for PCC, SSRP at 16 days and SSRP at 28 days, respectively.

7.3 Bonding Agents

Tables 7.10 through 7.12 summarize the bond coat comparison performance for PCC repair at 34 days and SSRP repair at 16 and 28 days, respectively. In these tables the epoxy coating, grout coating and no coating results were averaged between all surface conditioning methods for the same repair material.

Epoxy coating with PCC repair material performed better than having no bond agent but worse than a grout coating because the substrate failures rate was 25% for epoxy coating, 32% for grout coating and only 10% for no coating. Epoxy coating had the least substrate/interface failures with a rate of 44% while grout coating had a rate of

58% and no coating 83%. Epoxy coating had average bond strength of 217psi, grout coating average bond strength of 233psi and no coating had average bond strength of 195psi.

The epoxy coating completely failed when SSRP was applied over the coating. Most of the drilled cores broke at the interface and the four or five cores that did not break resulted in bond strength of less than 40psi. The mode of failure was at the interface between the epoxy and repair materials.

Grout coating outperformed no coating with SSRP material at 16 and 28 days. Substrate failure rates with grout coating were 41% and 73% at 16 and 28 days, respectively while no coating had substrate failure rates at 23% and 44% at 16 and 28 days, respectively. Substrate/interface failure rates with grout coating were 31% and 14% while no coating produced 19% and 39% failure rates at 16 and 28 days, respectively. Bond strengths did not change much for grout coating decreasing from 211psi to 203psi at 16 and 28 days, respectively. With no coating bond strength increased from 190psi to 225psi at 16 and 28 days respectively.

7.4 Repair Materials

Both the material properties and repair material mix can influence test results. In table 7.13 the results are summarized for each material at each pull date. The results from all surface conditioning methods and bond coats were averaged together for each respective material.

7.4.1 Repair Material PropertieS

Table 4.1 contains a summary of average compressive strength and modulus of all three materials as well as a percent difference in modulus from the substrate material. The 28-day compressive strength for the PCC mix was 6799psi. The 16-day compressive strength for the SSRP product was 6423psi and the 28-day strength 6155psi while the substrate material at 40 years of age is 4287psi. No correlation was shown by McDonald et al., (2002) between field performance and compressive strength of the substrate and repair materials.

The modulus difference between the PCC repair and substrate, SSRP at 16 days, SSRP at 28 days and the substrate material are 31.8%, 14.1% and 4.5% respectively. As the modulus differences decreased there is a decrease in substrate/interfacial failures and an increase in substrate failures when compared to overall results.

7.4.2 Repair Material Comparison

As shown in Table 7.13, substrate failure rates differed greatly between repair materials. Substrate failure rates were 21% for PCC and 60% for SSRP at similar pull dates. Substrate/interface failure rates were 63% for PCC and 25% for SSRP. Bond strength was 215psi for PCC and 214psi for SSRP.

Substrate failure rates increased from 33% at 16 days to 60% at 28 days for SSRP. Substrate/interface failure rates remained the same at 25%. Bond strength increased from 200psi at 16 days to 214psi at 28 days for SSRP.

A significant amount of voids were present at the repair/substrate interface with PCC repair material. Of the 86 interface failures, 41 of those had significant voids present with the vast majority when there was no bonding agent used. Figure 7.21 shows a typical core with voids present at the interface.

7.5 Overall PCC Repair Results

Table 7.14 presents complete results of surface conditioning method over specific bond coats. The best performer had the highest substrate failure rate followed by the lowest percentage of substrate/interface failures and then the highest bond strength.

Shot blasting with 230 and 330 steel sizes with grout coating as well as water-jetting at 40ksi produced good results. Shot blasting with 330 steel and a grout coat performed the best with 75% substrate failures, no substrate/interface failures, and bond strength of 265psi. Shot blasting with 230 steel and a grout coat was next with 67% substrate failures, 33% substrate/interface failures and bond strength of 227psi. Water-jetting at 40ksi with epoxy coating and grout coating resulted in 33% substrate failures and no substrate/interface failures. When there was no coat applied there was 50% failures in both the substrate and substrate/interface. Water-jetting with all bond coats resulted in high bond strengths at 218psi, 294psi and 261psi with no coat, grout coating and epoxy coating, respectively.

Sand blasting with the 8-20 mesh with epoxy coating and shot blasting with 230 steel and epoxy coating produced good results as well with substrate failure rates at 67% and 50%, respectively. However, bond strength for sand blasting with 8-20 mesh was the second lowest at only 156psi.

Water-jetting at 20ksi produced consistent results. Substrate failure rates were 25%, 14% and 0% with grout coating, no coating and epoxy coating, respectively. Substrate/interface failure rates were 75% and 43% with grout coating and no coating while epoxy coating produced 0% substrate/interface failures. Bond strength was 269psi, 218psi, and 223psi with grout coating, no coating and epoxy coating, respectively.

The rest of the combinations, especially when there was no coating performed poorly, with little or no substrate failures and high percentages of substrate/interface failures. Hammering was the worst performer with all bonding coats because it had no substrate failures, all substrate/interface failures and the lowest average bond strength.

7.6 Overall SSRP Repair results

Table 7.15 and 7.16 summarize performance rankings of all test matrix combinations for SSRP repair material at 16 and 28 days, respectively.

The most notable SSRP result was the poor performance of water-jetting at 40ksi with both grout coating and no coating. At 16 days with no coating the bond strength was 101psi, which is lower than minimum requirements and the lowest of all combinations. With a grout coating the bond strength was at 230psi but just as with no coating all the failures were new/interface. At 28 days the results were opposite. The grout coating strength decreased to 137psi and bond strength with no coating increased to 251psi. Failures went from 100% new/interface for the grout coating to 100% interfacial failures while with no coating new/interface failures decreased to 33%.

Water-jetting at 20ksi with a grout coating had consistent results as 75% substrate failures increased to 100%, there were no substrate/interface failures and the bond strength went from 198psi to 216psi for 16 and 28 day pulls, respectively. With no coating the results were not consistent as substrate failures went from 75% at 16 days to only 33% at 28 days. Substrate/interface failures increased from 0% at 16 days to 67% at 28 days. Bond strength, however, increased from 229psi to 253psi.

Shot blasting with 330 steel and no bond coat produced poor results with 100% and 75% substrate/interface failure rates at 16 and 28 days, respectively. Shot blasting with 330 steel and grout coating produced inconsistent results as substrate failures decreased over time from 100% at 16 days to 33% at 28 days.

Shot blasting with 230 steel and both bond coats had increasing performance over time. There was a 25% increase in substrate failure from 16 days to 28 days for grout coating and no coating, a 25% increase in substrate/interface failures with grout coating and no change in bond strength with a grout coat and a 50psi decrease in bond strength with no coating.

Sand blasting with the 60 mesh produced good results as substrate failure rates increased, substrate/interface failures decreased and bond strengths increased over time. Grout coating substrate failure rates increased from 0% to 100%, substrate/interface failure rates decreased from 67% to 0% and bond strength remained very high at 290psi and 277psi at 16 and 28 days, respectively. With no coating, substrate failure rates remained at 100% and bond strength increased from 236psi at 16 days to 299psi at 28 days.

Sand blasting with 8-20 mesh and grout coating had the most consistent results. At 16 days all failures were in the substrate at an average strength of 170psi. At 28 days all failures remained within the substrate and bond strength increased to 202psi. When there was no coating applied, substrate failures increased from 50% at 16 days to 67% at 28 days, substrate interface failures never occurred and bond strength increased 14psi. The average bond strength for sand blasting with 8-20 mesh with both coatings was the second lowest with the SSRP repair at only 170psi.

8. Discussion of results

8.1 Surface Conditioning

Surface conditioning involves removal of surface contaminants and micro-cracking and sufficiently roughening the surface. The effects of substrate roughness as produced by surface conditioning methods will be discussed followed by individual surface conditioning methods.

8.1.1 Surface Roughness

With PCC repair material there is no correlation between roughness and substrate failure rate (Figure 7.9). However, there is a strong correlation between increasing roughness and decreasing substrate/interface failure rates (Figure 7.10) indicating that water-jetting at 20ksi and 40ksi performed well at removing micro-cracking introduced by mechanical hammering. There is also a correlation between increasing roughness and increase in bond strength (Figure 7.11) possibly due to greater contact area because of the rougher surface.

With SSRP repair material at 28 days there is a correlation between decreasing substrate failure rates and increasing roughness (Figure 7.12) possibly due to the rapid setting SSRP not being able to penetrate deep voids in a rough surface. There was no correlation between roughness and substrate/interface failures (Figure 7.13) and between roughness and bond strength (Figure 7.14).

Water-jetting at 40ksi produced the roughest surface but had the poorest results with the SSRP repair material as opposed to the second best results with PCC repair material. This difference is probably because of the repair materials and how they interact with rough surfaces. The PCC had time to penetrate the pores because it hardened slowly while the rapid setting SSRP set so fast it could not penetrate the pores and adhere to the substrate. Even with a grout coating, 100% of the failures occurred at the repair/interface at 16 days and at the interface at 28 days also indicating that the SSRP repair material did not properly adhere to the substrate with the rough surface produced by the 40ksi water-jetting.

It was expected that the rougher the surface the better the results or that at least some type of pattern would develop but the amount of variables present had an impact. The only way to find any correlation was examining at the two repair material results separately and the results are opposites of each other as demonstrated by the results from water-jetting at 40ksi.

8.1.2 Surface conditioning methods

Considering surface conditioning methods as a whole there was no correlation between substrate failure rates and bond strength (Figures 7.15, 7.16, and 7.17). There was a slight trend for PCC and SSRP at 28 days as substrate failure rates increased bond strength increased.

With PCC repair material there was a correlation between increasing substrate/interface failure rates and decrease in bond strength. The opposite trend existed with SSRP repair material at 16days with bond strength increasing with substrate/interface failure rates. At 28 days there was no correlation between bond strength and substrate/interface failure rates.

Sand blasting with 8-20 mesh ranked in the top three for all pull tests. Substrate failures were 25%, 80% and 88% for PCC and SSRP at 16 and 28 days respectively. At the same time it had the second lowest, lowest and second lowest bond strength for PCC and SSRP at 16 and 28 days, respectively demonstrating that there is no correlation between percentage of substrate failure and bond strength.

Besides sand blasting with 8-20 mesh, there was no other surface conditioning method that performed well during all three pulls. The only other factor observed is that hammering always performed poorly, ranking last with PCC and second to last with SSRP.

The SSRP repair material results improved over time as expected. The only inconsistency is that sand blasting with 60 mesh increased from the fifth spot to the first spot. The other surface conditioning methods results increased in percentage substrate failures and bond strength.

When comparing sand to shot blasting with PCC repair material the smallest shot size performed the best while the smallest sand size performed the worst indicating no correlation between size of abrasive and performance. At 28 days, sand blasting outperformed shot blasting with higher percentage substrate failures but no correlation between bond strengths.

Abrasive blasting and hammering resulted in high levels of substrate/interface failures with PCC repair material. This fact demonstrates that both methods are not effective in removing micro-cracking. Except for shot blasting with 230 steel, which resulted in 58% failure, all the other abrasive blasting and hammering specimens experienced substrate/interface failure rates of 75% or more. Water-jetting at 20ksi and 40ksi resulted in substrate/interface failure rates of 38% and 15%, respectively indicating that water-jetting is more effective at removing micro-cracking.

SSRP hammering resulted in 67% substrate/interface failures. Only shot blasting with 330 steel had high levels of substrate/interface failures at 50% for 16 days and 71% for 28 days. There is a noticeable difference in performance between surface conditioning methods at removing micro-cracking with corresponding repair materials.

8.2 Bonding Coats

As discussed in Section 2, Li et al., (2001) noticed from SEM that there was only one interface between repair and substrate materials with a binder when specimens were placed on a vibrating table during application of the binder. However, upon visual inspection of the specimens of this research epoxy coating and grout coating could be seen as a fine line between the substrate and repair material (Figure 8.1 and 8.2). The extent that a vibrating table would compact a concrete specimen is unlikely to occur in field application.

Epoxy coating completely failed with SSRP, which might be due to the fact that SSRP product sets faster than the epoxy. The epoxy was scrubbed into the substrate but the repair mix was not scrubbed into the epoxy resulting in a better bond between the epoxy and substrate and a weak bond between epoxy and SSRP leading to the complete failure within the epoxy. There could have also been an adverse chemical reaction between SSRP and the epoxy coating. Epoxy can be difficult to handle and use and sensitive to many conditions as noted by Maerz et al., (2001). Epoxy coating did not perform exceptionally well with the PCC material as well. The fact that it was a three-part epoxy could have had an effect on the results.

Grout coating with PCC resulted in 32% substrate failures as opposed to 25% substrate failures for epoxy coating. Grout coating with SSRP performed excellent, resulting in 41% substrate failures at 16 days and 73% substrate failures at 28 days. With both repair materials, it was the grout coating that resulted in the highest percentage of substrate failures.

When there was no coating applied the results were always the poorest. With no coating there were 10%, 23% and 44% substrate failures with PCC and SSRP at 16 and 28 days respectively.

There was a significant amount of substrate/interface failures when there was no coating with PCC repair. With a bond coating and PCC repair material there was a decrease in substrate/interface failures. Such a fact is probably not a reflection on the quality or type of coating used but just that it was scrubbed into the substrate increasing adhesion between repair and substrate materials. This procedure caused more substrate failures because the bonding coat penetrated the pores of the substrate bypassing the bruised layer.

With SSRP, the grout coating offset possible failure due to micro-cracking resulting in more substrate failures. The fact that the grout coating for SSRP was actually SSRP scrubbed into the substrate helped with adhesion to the substrate and penetration of the grout into the pores, which is evidenced by the decrease of substrate/interface failures from 31% to 14% between pulls. The opposite was true when there was no coating with SSRP. There were 35% new/interface failures at 16 days and only 19% substrate/interface failures. New/interface failures at 28 days decreased to 11% and substrate/interface failures increased to 39%. These results can possibly be explained by the fact that the SSRP was still hardening at 16 days and hadn't quite adhered to the substrate. At 28 days, it had hardened and adhered to the substrate surface sufficiently such that it was less sensitive to insufficient surface conditioning.

There were also a lot of voids present when there was no coating with PCC repair material. This fact indicates poor compaction and iterates the fact that if repair concrete is just placed on substrate material with no coating and no scrubbing it cannot be assumed that it will completely adhere to the substrate material, even with SSD condition

8.3 Repair Materials

SSRP outperformed PCC repair material with higher percentage substrate failures and less percentage substrate/interface failures. The average bond strength was approximately about the same for both materials. Even though the bond strengths were about the same, failure modes were completely different. Another factor to consider is that the grout coating for PCC was cement and water and did not have the same material properties as the PCC repair material. With the SSRP, the grout coating had the same material properties as the repair material which could have helped prevent any material mismatch problems within the repair/bond agent interface. Even when there was no bonding agent SSRP still outperformed PCC as a repair material. SSRP performed much better at adhering to the substrate material because of the absence of voids but at the same time it did not result in higher bond strengths.

Because grout coating was somewhat different and SSRP completely failed with epoxy coating, the only way to compare the two mixes was when there was no coating. In this case, SSRP outperformed PCC. SSRP was better at adhering to the substrate and resulted in more substrate failures. There was also an increase in bond strength from 195psi for PCC to 225psi for SSRP. There were no visible voids present at SSRP interfaces as there were with PCC.

As percent modulus difference decreased between repair and substrate materials the percentage of substrate failures increased. As Austin et al., (1995) noted, a difference in modulus creates stress concentrations at the bond interface. PCC had the highest difference in modulus at 31.8% and also had the most interfacial failures. SSRP, at 28 days had the lowest percentage modulus difference at 4.5% and had the least interfacial failures.

8.4 Overall PCC Results

When there was no bonding agent, the majority of the failures occurred at the substrate/interface level. Significant voids were present in almost every circumstance. As far as abrasive blasting, no matter what type of bonding coat was used, the majority of them had high percentage substrate/interface failures indicating inadequate removal of micro-cracking caused by mechanical hammering and lower than average bond strengths. Of the 12 abrasive combinations, only three had percentage substrate failures that were higher than percentage substrate/interface failures. Sand blasting with 8-20 mesh and epoxy coating might have had a high percentage substrate failure rate but the bond strength was only 156psi. Shot blasting with 230 and 330 steel and grout coating were the only abrasive blasting combinations that were adequate. These combinations resulted in higher than average bond strengths and had high percentage substrate failures.

Water-jetting at 40ksi produced the most consistent results with all bonding coats finishing fifth, sixth and seventh. Of the three bond coat possibilities only no coating produced substrate/interface failures, which could be due to the fact that because of the rough surface the voids were not filled and resulted in areas of weakness. With grout and epoxy coatings, 33% of the specimens experienced substrate failures; the rest experienced either interface failures or new/interface failures. This could be due to the fact that the epoxy and grout coatings bonded better with the substrate than the repair material bonded with them. Water-jetting at 40ksi with a grout coating produced the highest bond strength at 294psi and with epoxy it produced the fourth highest at 261psi. When there was no coating there were substrate failures but lower bond strength than that of epoxy and grout coatings, which further shows that there was no correlation between mode of failure and bond strength.

Neglecting the specimens with no coating, shot blasting with 230 steel performed somewhat consistently. The average strength with grout and epoxy coatings were both at about 225psi as well as with percent substrate failures of 67% and 50%, respectively. This could be more of a reflection on the state of the substrate material than anything else. PCC repair material was not proven to result in high percentage substrate failures. The mtd of shot blasting with 230 steel only increased .004in from that of hammering. These results were probably a combination of factors and not necessarily the result of shot blasting with 230 steel alone.

8.5 Overall SSRP Results

One would expect that if that everything stayed the same, the best performers of SSRP at 16 days would increase in performance and remain the best when tested again at 28 days. This is true for all circumstances except for shot blasting with 330 steel and a grout coating as well as water-jetting at 20ksi with no coating. All other combinations increased in percentage substrate failure and in bond strength except for sand blasting with the 60 mesh and grout coating, shot blasting with 230 steel and no coating and water-jetting at 40ksi with grout coating. However, sand blasting with 60 mesh and grout coating as well as shot blasting with 230 steel and no coating had increases in percentage substrate failure. Water-jetting at 40ksi with grout coating had a dramatic decrease in bond strength, from 230psi to 137psi with no improvement in mode of failure. The assumption that results improve over time is valid.

Although sand blasting with the 60 mesh did perform the best, the results might be misleading because of the difference in roughness between 15N1 and the rest of the slabs when SSRP repair material was applied. Because the surface of 15N1 was rougher it was harder to hammer the surface because of all the voids. If hammering did not impact all areas, the amount of micro-cracking would have been less, leading to less planes of weakness causing an increase in percentage substrate failures as well as bond strength.

Sand blasting with 8-20 mesh also had a rough surface but most of the pull tests were done in the outer areas where the surface had been cut by saw. A few pull tests were conducted in the rougher areas to determine if there was any difference. The results were comparable denying such a hypothesis. The thickness of repair material was different than that of the other specimens. The repair material had a 4 inch thickness. What effect this might have had on testing was not determined and a 2 inch thickness might have performed better or worse. Sand blasting with 8-20 mesh performed well also.

Water-jetting at 20ksi with a grout coating was the best performer with SSRP repair material. At 16 days, 75% of the failures were in the substrate increasing to 100% at 28 days. The bond strength also increased from 198psi at 16 days to 216psi at 28 days. When there was no bonding coating the percentage of substrate failure decreased from 75% to 33% but the bond strength increased from 229psi to 253psi. For some unknown reason, the bond strength was higher when there was no coating as opposed to grout coating but the grout coating resulted in more substrate failures, which again demonstrates the inconsistent nature of concrete.

9. Conclusions

Three types of surface preparation methods were tested with two different repair materials on forty-year old concrete taken from a deteriorated bridge bent. In addition, bonding agents were applied to determine if they had any improvements on bonding strength. Mechanical hammering was done on all surfaces prior to specific surface conditioning methods combined with bonding agents so that the method could be evaluated on how well micro-cracking was removed. Failure within the substrate was categorized as the most important determination of satisfactory performance. Bond strengths, surface roughness and modulus were also measured and used as ways to evaluate surface conditioning methods, bonding agent usefulness and repair material performance. The percentage of substrate/interface failures was used to determine the effectiveness of surface preparation methods to remove micro-cracking.

The following conclusions can be drawn from the results of this study:

1. No correlation between the mode of failure and bond strength could be determined. No matter what type of comparison were used, whether it was the average results from a single repair mix, the average results from bonding agents, the average results from surface conditioning methods or individual results, a correlation between the mode of failure and bond strength could be not determined. There was a modest correlation between substrate/interface failure rates and bond strength for PCC repair material but because it is the only correlation, conclusions can not be drawn.

2. There is a correlation between roughness and substrate/interface failure rates as well as roughness and bond strength if the results from the PCC repair material were examined by themselves. As the surface increases in roughness fewer failures will occur due to micro-cracking and higher the bond strengths will result if PCC repair material is used. These same correlations did not exist with SSRP repair material.

3. Additional surface preparation needs to take place if mechanical hammering is used as a method for removing deteriorated concrete. Hammering as a method of surface preparation resulted in interfacial failures, especially at the substrate/interfacial. It also resulted in the lowest bond strength average with PCC repair material and the third lowest with SSRP repair material.

4. No conclusion can be made as to what type of surface conditioning method should be used although water-jetting performed consistently.

5. Grout coating outperformed all bond coatings. The procedure resulted in higher rates of percentage substrate failures but did not result in significantly higher pull strengths. Just applying repair material to substrate material without some type of scrubbing is not sufficient. This was evident throughout all tests when there were no coating applied, especially with PCC repair material.

6. If a bonding agent rather than grout coating is used, matching the bonding agent to both the repair and repaired material is crucial as evidenced by the complete failure of the SSRP bonding to the epoxy coating.

10. References

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Tables

Table 3.1 Slab Areas and Surface Preparation Methods

Slab	Approx. Surface Area	Surface Preparation
15N1	24in x 37in	60 grain Sand
15N2	27in x 39in	330 Shot
15N3	27in x 39in	230 Shot
15N4	26in x 41in	40 ksi water
15N5	27in x 40in	20 ksi water
15NB	27in x 32in	8-20 grain Sand
15NE	18in x 18in	Bush hammer only

Table 4.1 Compressive Strength and Modulus Comparisons

Specimen	Compressive Strength (psi)	Modulus (ksi)	% Difference from old
Substrate	4286.54	847.30	
PCC Repair (28 days)	6799.23	1116.75	31.80
SSRP Repair (16 days)	6423.23	966.51	14.07
SSRP Repair (28 days)	6155.41	885.57	4.52

Table 4.2 Portland Cement Concrete Repair Mix Specifications

Ingredients	Type/Brand	Weight		Yield (ft^3)
Water		4 to 5	gallons	0.6
Air Entrainment	Daravair 1000 - 6-8% agent	0.5	oz.	0.24
Midrange Water Reducer	WRDA 35	3	oz.	-
Cement	Portland Type I and II	94	lbs.	0.48
Fly Ash	Type F	15	lbs.	0.08
Pea Gravel	#8	194	lbs.	1.17
Sand	Concrete Sand by Quikrete (used by UDOT)	194	lbs.	1.16
				3.73

Table 7.1 Test Matrix

Concrete Mix	Prep Method	Bonding Agent	Samples
High Performance Portland Cement	Waterjetting 20ksi	Nothing	6
		Grout	6
		Epoxy	6
	Waterjetting 40ksi	Nothing	6
		Grout	6
		Epoxy	6
	Shot blasting 230 Steel Shot	Nothing	6
		Grout	6
		Epoxy	6
	Shot blasting 330 Steel Shot	Nothing	6
		Grout	6
		Epoxy	6
	Sand blasting 60 Mesh	Nothing	6
		Grout	6
		Epoxy	6
	Sand blasting 8-20 Mesh	Nothing	6
		Grout	6
		Epoxy	6
	Hammer Bush bit	Nothing	4
		Grout	4
		Epoxy	4
SSRP Product Rapid Set	Waterjetting 20ksi	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*
	Waterjetting 40ksi	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*
	Shot blasting 230 Steel Shot	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*
	Shot blasting 330 Steel Shot	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*
	Sand blasting 60 Mesh	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*
	Sand blasting 8-20 Mesh	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*
	Hammer Bush bit	Nothing	8*
		Scrub Coat	8*
		Epoxy	8*

* Four for 14-day strength and four for 28-day strength

Table 7.2 PCC 34-Day Direct Tensile Test Summary of Results

Bent	15N End			15N Base			15N 1			15N 2			15N3		
Surface Conditioning	Hammer			Sand blast 8-20 mesh			Sand blast 60 mesh			Shot blast 330 steel			Shot blast 230 steel		
Binder	Epoxy	Grout	Nothing	Epoxy	Grout	Nothing	Epoxy	Grout	Nothing	Epoxy	Grout	Nothing	Epoxy	Grout	Nothing
Bond Strength (psi)	160	167	122	156	164	171	243	244	217	253	265	193	224	227	224
Bond Strength (lbs)	948	990	724	925	976	1014	1442	1448	1291	1505	1573	1149	1330	1348	1333
S.D.	293	201	135	204	115	143	111	328	184	273	152	151	315	275	233
C.V.	31	20	19	22	12	14	8	23	14	18	10	13	24	20	17
No. of Samples	4	3	5	6	5	5	5	6	7	4	4	7	6	6	7
Failure in: New															
New/Interface							1								
Interface							1				1				
Substrate/Interface	4	3	5	2	5	5	3	5	7	4		7	3	2	6
Substrate				4				1			3		3	4	1
Voids Present			5			4		1	7		1	7		2	2
% New	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
% New/Interface	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0
% Interface	0	0	0	0	0	0	20	0	0	0	25	0	0	0	0
% Substrate/Interface	100	100	100	33	100	100	60	83	100	100	0	100	50	33	86
% Substrate	0	0	0	67	0	0	0	17	0	0	75	0	50	67	14

Table 7.2 (Cont.) PCC 34-Day Direct Tensile Test Summary of Results

Bent	15N4			15N5		
Surface Conditioning	Waterjet 40ksi			Waterjet 20ksi		
Binder	Epoxy	Grout	Nothing	Epoxy	Grout	Nothing
Bond Strength (psi)	261	294	218	223	269	218
Bond Strength (lbs)	1548	1743	1293	1326	1600	1293
S.D.	329	223	236	256	115	236
C.V.	21	13	18	19	7	18
No. of Samples	6	3	4	5	4	7
Failure in: New						
New/Interface	2			4		
Interface	2	2		1		3
Substrate/Interface			2		3	3
Substrate	2	1	2		1	1
Voids Present		2	3		1	6
% New	0	0	0	0	0	0
% New/Interface	33	0	0	80	0	0
% Interface	33	67	0	20	0	43
% Substrate/Interface	0	0	50	0	75	43
% Substrate	33	33	50	0	25	14

Table 7.3 SikaSet Roadway Patch 2000 16-Day Direct Tensile Test Summary of Results

Bent	15N End		15N Base		15N 1		15N 2		15N3		15N4		15N5	
Surface Conditioning	Hammer		Sand blast 8-20 Mesh		Sand blast 60 Mesh		Shot blast 330 Steel		Shot blast 230 Steel		Waterjet 40ksi		Waterjet 20ksi	
Binder	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing
Bond Strength (psi)	199	180	170	155	290	236	201	221	187	203	230	101	198	229
Bond Strength (lbs)	1181	1072	1010	920	1723	1400	1195	1310	1113	1204	1365	600	1175	1358
S.D.	151	237	80	283	315	0	148	84	102	92	53	175	339	156
C.V.	13	22	8	31	18	0	12	6	9	8	4	29	29	12
No. of Samples	7	5	3	2	3	1	4	4	4	4	4	6	4	4
Failure in: New					1									
New/Interface				1						2	4	6		
Interface		4							2	1			1	1
Substrate/Interface	7	1			2			4						
Substrate			3	1		1	4		2	1			3	3
% New	0	0	0	0	33	0	0	0	0	0	0	0	0	0
% New/Interface	0	0	0	50	0	0	0	0	0	50	100	100	0	0
% Interface	0	80	0	0	0	0	0	0	50	25	0	0	25	25
% Substrate/Interface	100	20	0	0	67	0	0	100	0	0	0	0	0	0
% Substrate	0	0	100	50	0	100	100	0	50	25	0	0	75	75

Table 7.4 SikaSet Roadway Patch 2000 28-Day Direct Tensile Test Summary of Results

Bent	15N Base		15N 1		15N 2		15N3		15N4		15N5	
Surface Conditioning	Sand blast 8-20 Mesh		Sand blast 60 Mesh		Shot blast 330 Steel		Shot blast 230 Steel		Waterjet 40ksi		Waterjet 20ksi	
Binder	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing	Grout	Nothing
Bond Strength (psi)	202	169	277	299	201	223	183	152	137	251	216	253
Bond Strength (lbs)	1202	1007	1647	1777	1197	1325	1088	900	813	1493	1280	1503
S.D.	165	401	130	211	367	251	203	141	280	83	331	339
C.V.	14	40	8	12	31	19	19	16	34	6	26	23
No. of Samples	5	3	3	3	3	4	4	2	3	3	4	3
Failure in: New												
New/Interface										2		
Interface								1	3			
Substrate/Interface		1			2	3	1			1		2
Substrate	5	2	3	3	1	1	3	1			4	1
% New	0	0	0	0	0	0	0	0	0	0	0	0
% New/Interface	0	0	0	0	0	0	0	0	0	67	0	0
% Interface	0	0	0	0	0	0	0	50	100	0	0	0
% Substrate/Interface	0	33	0	0	67	75	25	0	0	33	0	67
% Substrate	100	67	100	100	33	25	75	50	0	0	100	33

Table 7.5 Surface Conditioning Method Results for PCC 34-Day Repair

Surface Conditioning	Shot blast 230 shot	Waterjet 40ksi	Sand blast 8-20 mesh	Shot blast 330 shot	Waterjet 20ksi	Sand blast 60 mesh	Hammer
Bond Strength (psi)	225	257	164	237	237	235	149
Bond Strength (lbs)	1337	1528	972	1409	1406	1394	887
S.D.	10	226	45	228	169	89	143
C.V.	1	15	5	16	12	6	16
No. of Samples	19	13	16	15	16	18	12
Failure in: New	0	0	0	0	0	0	0
New/Interface	0	2	0	0	4	1	0
Interface	0	4	0	1	4	1	0
Substrate/Interface	11	2	12	11	6	15	12
Substrate	8	5	4	3	2	1	0
Voids Present	4	5	4	8	7	8	5
% New	0	0	0	0	0	0	0
% New/Interface	0	15	0	0	25	6	0
% Interface	0	31	0	7	25	6	0
% Substrate/Interface	58	15	75	73	38	83	100
% Substrate	42	38	25	20	13	6	0
Surface Roughness (mtd.)	0.047	0.096	0.046	0.049	0.072	0.053	0.043

Table 7.6 Surface Conditioning Method Results for SSRP 16-Day Repair

Surface Conditioning	Sand blast 8-20 mesh	Waterjet 20ksi	Shot blast 330 shot	Shot blast 230 shot	Sand blast 60 mesh	Hammer	Waterjet 40ksi
Bond Strength (psi)	162	213	211	195	263	190	165
Bond Strength (lbs)	965	1266	1253	1158	1562	1127	983
S.D.	64	129	81	65	229	77	541
C.V.	7	10	6	6	15	7	55
No. of Samples	5	8	8	8	4	12	10
Failure in: New	0	0	0	0	1	0	0
New/Interface	1	0	0	2	0	0	10
Interface	0	2	0	3	0	4	0
Substrate/Interface	0	0	4	0	2	8	0
Substrate	4	6	4	3	1	0	0
% New	0	0	0	0	25	0	0
% New/Interface	20	0	0	25	0	0	100
% Interface	0	25	0	38	0	33	0
% Substrate/Interface	0	0	50	0	50	67	0
% Substrate	80	75	50	38	25	0	0
Surface Roughness		0.053	0.046	0.042		0.041	0.070

Table 7.7 Surface Conditioning Method Results for SSRP 28-Day Repair

Surface Conditioning	Sand blast 60 mesh	Sand blast 8-20 mesh	Waterjet 20ksi	Shot blast 230 shot	Shot blast 330 shot	Waterjet 40ksi
Bond Strength (psi)	288	186	234	167	212	194
Bond Strength (lbs)	1712	1104	1392	994	1261	1153
S.D.	92	138	158	133	91	481
C.V.	5	13	11	13	7	42
No. of Samples	6	8	7	6	7	6
Failure in: New	0	0	0	0	0	0
New/Interface	0	0	0	0	0	2
Interface	0	0	0	1	0	3
Substrate/Interface	0	1	2	1	5	1
Substrate	6	7	5	4	2	0
% New	0	0	0	0	0	0
% New/Interface	0	0	0	0	0	33
% Interface	0	0	0	17	0	50
% Substrate/Interface	0	13	29	17	71	17
% Substrate	100	88	71	67	29	0
Surface Roughness			0.053	0.042	0.046	0.070

Table 7.8 Summary of Results for Roughness Tests for PCC side

Slab	Surface Preparation	Average D (in)	Average Mtd (in)
15N-End	Bush Hammer	7.16	0.043
15N-Base	8-20 Mesh Sand	6.91	0.046
15N-3	230 Steel Shot	6.84	0.047
15N-2	330 Steel Shot	6.72	0.049
15N-1	60 Mesh Sand	6.43	0.053
15N-5	20ksi Water jet	5.54	0.072
15N-4	40ksi Water jet	4.79	0.096

Table 7.9 Summary of Results for Roughness Tests for SSRP side

Slab	Surface Preparation	Average D (in)	Average Mtd (in)
15N-End	Bush Hammer	7.03	0.041
15N-3	230 Steel Shot	6.94	0.042
15N-2	330 Steel Shot	6.67	0.046
15N-5	20ksi Water jet	6.19	0.053
15N-4	40ksi Water jet	5.39	0.070

Table 7.10 Bond Coat Comparison for PCC 34-Day Repair

Binder	Epoxy	%	Grout	%	Nothing	%
Bond Strength (psi)	217		233		195	
No. Samples	36		31		42	
Failure in: New	0	0	0	0	0	0
New/Interface	7	19	0	0	0	0
Interface	4	11	3	10	3	7
Substrate/Interface	16	44	18	58	35	83
Old	9	25	10	32	4	10

Table 7.11 Bond Coat Comparison for SSRP 16-Day Repair

Binder	Scrub	%	Nothing	%
Bond Strength (psi)	211		190	
No. Samples	29		26	
Failure in: New	1	3	0	0
New/Interface	4	14	9	35
Interface	3	10	6	23
Substrate/Interface	9	31	5	19
Old	12	41	6	23

Table 7.12 Bond Coat Comparison for SSRP 28-Day Repair

Binder	Scrub	%	Nothing	%
Bond Strength (psi)	203		225	
No. Samples	22		18	
Failure in: New	0	0	0	0
New/Interface	0	0	2	11
Interface	3	14	1	6
Substrate/Interface	3	14	7	39
Old	16	73	8	44

Table 7.13 Repair Mix Performance Comparison

Repair Mix	SSRP 28-Day	SSRP 16-Day	PCC 34-Day
Bond Strength (psi)	214	200	215
Bond Strength (lbs)	1269	1188	1276
S.D.	296	259	265
C.V.	23	22	21
No. of Samples	40	55	109
Failure in: New	0	1	0
New/Interface	2	13	7
Interface	4	9	10
Substrate/Interface	10	14	69
Substrate	24	18	23
Voids Present	0	0	41
% New	0	2	0
% New/Interface	5	24	6
% Interface	10	16	9
% Substrate/Interface	25	25	63
% Substrate	60	33	21

Table 7.14 Ranked Results for PCC 34-Day Repair

Surface Conditioning	Shot 330	Shot 230	Sand 8-20		Water 40ksi	Water 40ksi	Water 40ksi	Water 20ksi	Sand 60	Water 20ksi	Shot 230
Binder	Grout	Grout	Epoxy	Shot 230 Epoxy	Nothing	Grout	Epoxy	Grout	Grout	Nothing	Nothing
Bond Strength (psi)	265	227	156	224	218	294	261	269	244	218	224
Bond Strength (lbs)	1573	1348	925	1330	1293	1743	1548	1600	1448	1293	1333
S.D.	152	275	204	315	236	223	329	115	328	236	233
C.V.	10	20	22	24	18	13	21	7	23	18	17
No. of Samples	4	6	6	6	4	3	6	4	6	7	7
Failure in: New	0	0	0	0	0	0	0	0	0	0	0
New/Interface	0	0	0	0	0	0	2	0	0	0	0
Interface	1	0	0	0	0	2	2	0	0	3	0
Substrate/Interface	0	2	2	3	2	0	0	3	5	3	6
Substrate	3	4	4	3	2	1	2	1	1	1	1
Voids Present	1	2	0	0	3	2	0	1	1	6	2
% New	0	0	0	0	0	0	0	0	0	0	0
% New/Interface	0	0	0	0	0	0	33	0	0	0	0
% Interface	25	0	0	0	0	67	33	0	0	43	0
% Substrate/Interface	0	33	33	50	50	0	0	75	83	43	86
% Substrate	75	67	67	50	50	33	33	25	17	14	14

Table 7.14 (Cont.) Ranked Results for PCC 34-Day Repair

Surface Conditioning	Water 20ksi	Sand 60	Shot 330	Sand 60		Sand 8-20		Sand 8-20	Hammer	
Binder	Epoxy	Epoxy	Epoxy	Nothing	Shot 330 Nothing	Nothing	Hammer Grout	Grout	Epoxy	Hammer Nothing
Bond Strength (psi)	223	243	253	217	193	171	167	164	160	122
Bond Strength (lbs)	1326	1442	1505	1291	1149	1014	990	976	948	724
S.D.	256	111	273	184	151	143	201	115	293	135
C.V.	19	8	18	14	13	14	20	12	31	19
No. of Samples	5	5	4	7	7	5	3	5	4	5
Failure in: New	0	0	0	0	0	0	0	0	0	0
New/Interface	4	1	0	0	0	0	0	0	0	0
Interface	1	1	0	0	0	0	0	0	0	0
Substrate/Interface	0	3	4	7	7	5	3	5	4	5
Substrate	0	0	0	0	0	0	0	0	0	0
Voids Present	0	0	0	7	7	4	0	0	0	5
% New	0	0	0	0	0	0	0	0	0	0
% New/Interface	80	20	0	0	0	0	0	0	0	0
% Interface	20	20	0	0	0	0	0	0	0	0
% Substrate/Interface	0	60	100	100	100	100	100	100	100	100
% Substrate	0	0	0	0	0	0	0	0	0	0

Table 7.15 Ranked Results for SSRP 16-Day Repair

Surface Conditioning / Binder	Sand 60 Nothing	Shot 330 Grout	Sand 8-20 Grout	Water 20ksi Nothing	Water 20ksi Grout	Shot 230 Grout	Sand 8-20 Nothing	Shot 230 Nothing	Water 40ksi Nothing
Bond Strength (psi)	236	201	170	229	198	187	155	209	101
Bond Strength (lbs)	1400	1195	1010	1358	1175	1113	920	1243	600
S.D.	0	148	80	156	339	102	283	39	175
C.V.	0	12	8	12	29	9	31	8	29
No. of Samples	1	4	3	4	4	4	2	4	6
Failure in: New	0	0	0	0	0	0	0	0	0
New/Interface	0	0	0	0	0	0	1	2	6
Interface	0	0	0	1	1	2	0	1	0
Substrate/Interface	0	0	0	0	0	0	0	0	0
Substrate	1	4	3	3	3	2	1	1	0
% New	0	0	0	0	0	0	0	0	0
% New/Interface	0	0	0	0	0	0	50	50	100
% Interface	0	0	0	25	25	50	0	25	0
% Substrate/Interface	0	0	0	0	0	0	0	0	0
% Substrate	100	100	100	75	75	50	50	25	0

Table 7.15 (Cont.) Ranked Results for SSRP 16-Day Repair

Surface Conditioning / Binder	Water 40ksi Grout	Hammer Nothing	Sand 60 Grout	Shot 330 Nothing	Hammer Grout
Bond Strength (psi)	230	180	290	221	199
Bond Strength (lbs)	1365	1072	1723	1310	1181
S.D.	53	237	315	84	151
C.V.	4	22	18	6	13
No. of Samples	4	5	3	4	7
Failure in: New	0	0	1	0	0
New/Interface	4	0	0	0	0
Interface	0	4	0	0	0
Substrate/Interface	0	1	2	4	7
Substrate	0	0	0	0	0
% New	0	0	33	0	0
% New/Interface	100	0	0	0	0
% Interface	0	80	0	0	0
% Substrate/Interface	0	20	67	100	100
% Substrate	0	0	0	0	0

Table 7.16 Ranked Results for SSRP 28-Day Repair

Surface Conditioning	Sand 60	Sand 60	Water 20ksi	Sand 8-20	Shot 230	Sand 8-20	Shot 230	Water 20ksi	Shot 330	Shot 330	Water 40ksi	Water 40ksi
Binder	Nothing	Grout	Grout	Grout	Grout	Nothing	Nothing	Nothing	Grout	Nothing	Grout	Nothing
Bond Strength (psi)	299	277	216	202	183	169	152	253	201	223	137	251
Bond Strength (lbs)	1777	1647	1280	1202	1088	1007	900	1503	1197	1325	813	1493
S.D.	211	130	331	165	203	401	141	339	367	251	280	83
C.V.	12	8	26	14	19	40	16	23	31	19	34	6
No. of Samples	3	3	4	5	4	3	2	3	3	4	3	3
Failure in: New	0	0	0	0	0	0	0	0	0	0	0	0
New/Interface	0	0	0	0	0	0	0	0	0	0	0	2
Interface	0	0	0	0	0	0	1	0	0	0	3	0
Substrate/Interface	0	0	0	0	1	1	0	2	2	3	0	1
Substrate	3	3	4	5	3	2	1	1	1	1	0	0
% New	0	0	0	0	0	0	0	0	0	0	0	0
% New/Interface	0	0	0	0	0	0	0	0	0	0	0	67
% Interface	0	0	0	0	0	0	50	0	0	0	100	0
% Substrate/Interface	0	0	0	0	25	33	0	67	67	75	0	33
% Substrate	100	100	100	100	75	67	50	33	33	25	0	0

FIGURES

Figure 3.1. Locations of Specimen Removal

Figure 3.2. Wire Sawing Setup

Figure 3.3. Typical Slab

Figure 3.4. Mechanical Hammer and Bush Bit

Figure 3.5. Hammered vs. Sawn Surface Comparison

Figure 3.6. 15N4 aster 40ksi Water-jetting Preparation

Figure 3.7. 15N5 after 20ksi Water-jetting Preparation

Figure 3.8. Nozzle used for Water-jetting

Figure 3.9. Gyro Gun in Use

Figure 3.10. 8-20 Mesh Silica Abrasive used for Sand Blasting

Figure 3.11. 60 Mesh Ruby Garnet Abrasive

Figure 3.12. 15NB after Sand Blasting with size 8 –20 mesh

Figure 3.13. 15N1 after Sand Blasting with size 60 mesh

Figure 3.14. Sand Blasting Equipment

Figure 3.15. 15N2 after Shot Blasting with 330 Steel

Figure 3.16. 15N3 after Shot Blasting with 230 Steel

Figure 3.17. Amasteel Cast Steel Shot used for Shot Blasting

Figure 3.18. Blastrac Shot Machine

Figure 3.19. Cleaning with Pressurized Water

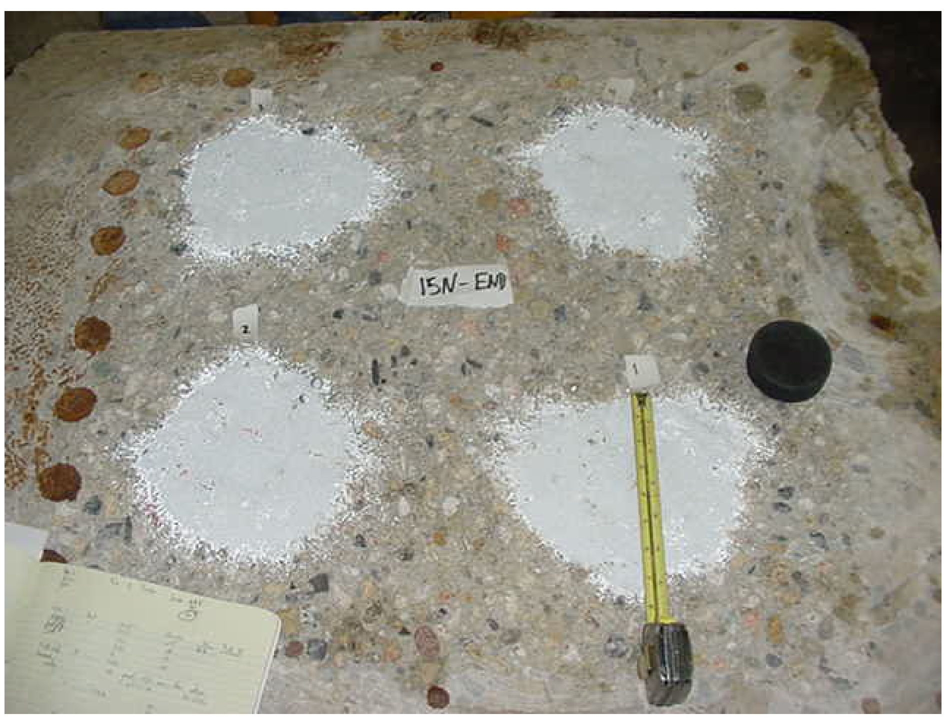


Figure 3.20. Basic Layouts for Roughness Tests

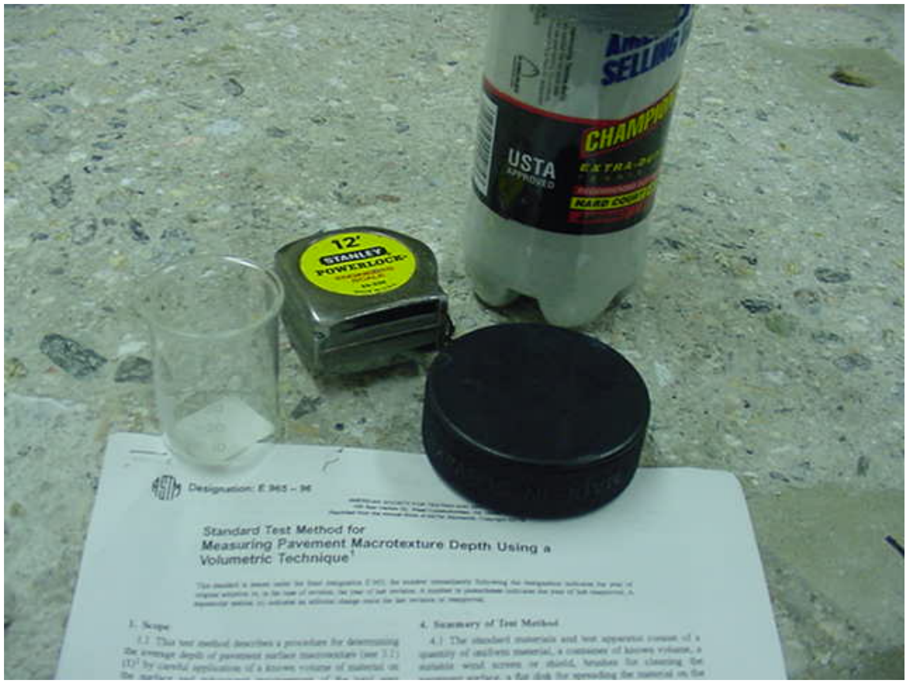


Figure 3.21. Roughness Test Instruments

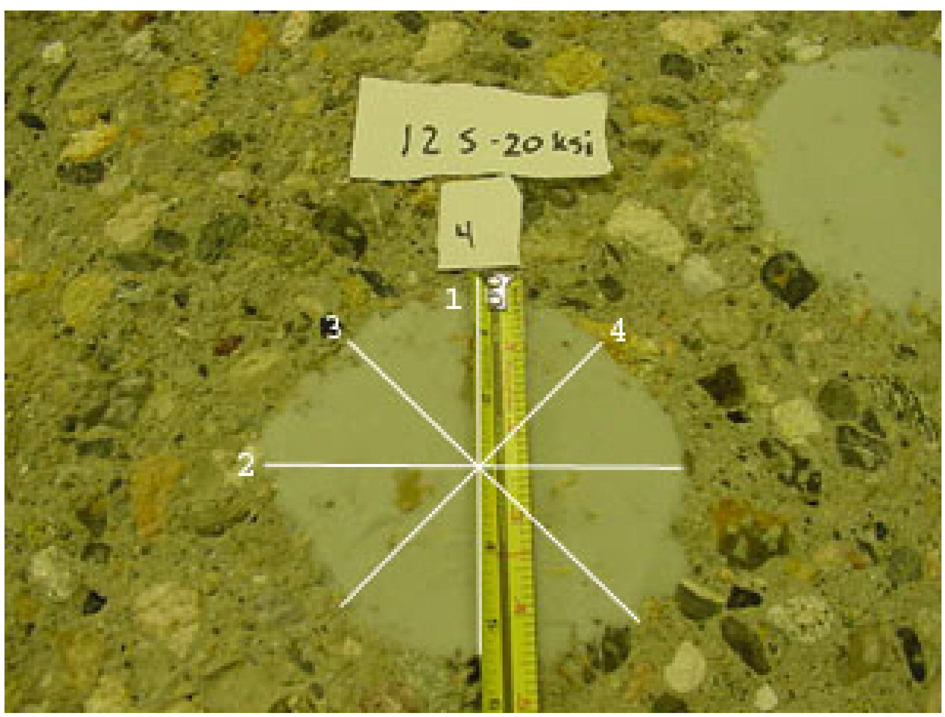


Figure 3.22. Diameter Measurement Locations and Ordering

Figure 3.23. Pre-wetting of 15N2 to Achieve SSD Conditions

Figure 3.24. SSD Conditions on 15N2 before Applying SSRP

Figure 4.1. Application of PCC Repair Material to Substrate

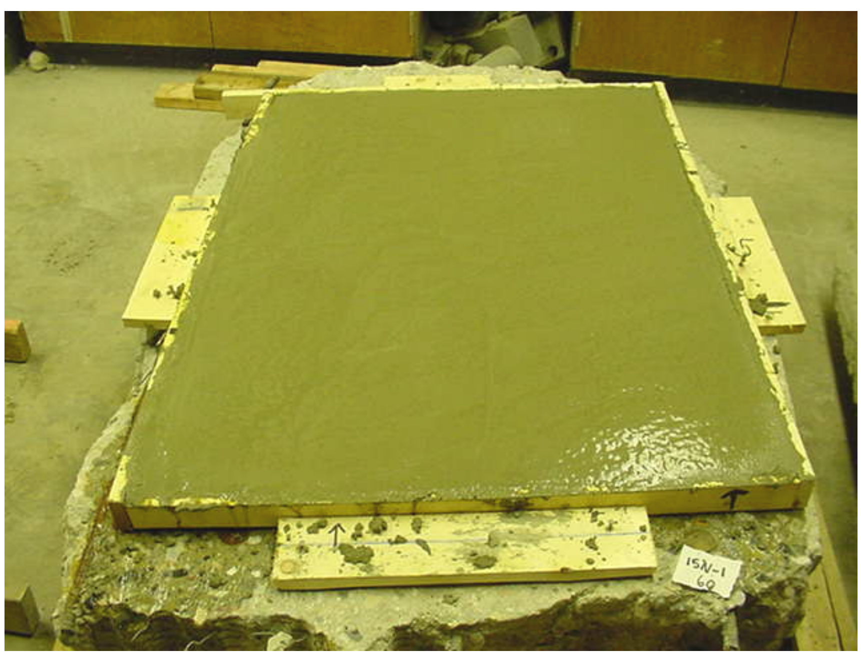


Figure 4.2. Finished PCC Repair Material on 15N1

Figure 4.3. Applying SSRP Repair Material to 15N3

Figure 4.4. Finished SSRP Material on 15N3

Figure 4.5. Typical Layouts of Bond Coats

Figure 4.6. Application of Water to Maintain SSD Conditions

Figure 4.7. Mixing Epoxy

Figure 4.8. Typical Application of Epoxy on SSD Substrate

Figure 4.9. Mixing Grout for PCC Repair Material

Figure 4.10. Scrubbing in PCC Grout into Substrate

Figure 4.11. Scrubbing in SSRP Grout into Substrate

Figure 4.12. Compaction with a Hand Trowel

Figure 4.13. Curing of PCC Repairs

Figure 5.1. Milwaukee Dymodrill with Diamond Bit used for Coring

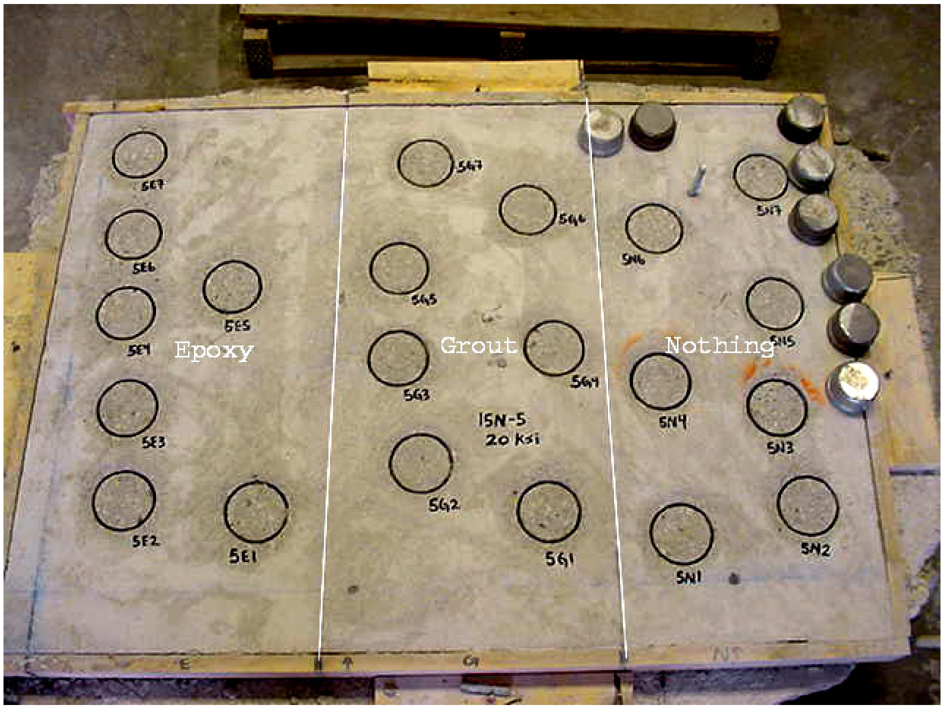


Figure 5.2. Typical Layouts of Cores for Testing

Figure 5.3. Grinding the Tops of the Cores

Figure 5.4. Pull Tester Provided by Restruction Corp.

Figure 5.5. Close-up of Pull Tester Gage

Figure 5.6. Pull Tester Set-up

Figure 5.7. Pull Test Bit Screwed into Steel Cap Epoxied onto Core

Figure 5.8. Applying Epoxy to Top of Grinded and Cleaned Core

Figure 5.9. Applying Steel Cap to Core

Figure 5.10. Pull Tester during Testing

Figure 6.1. 15NB Rough Surface for SSRP Repair

Figure 6.2. 15N1 Area Used for Testing

Figure 6.3. Comparison of Time of Exposure for Water-jetting at 40ksi

Figure 6.4. Dust Collected by Sand Blaster After All Surface Completed

Figure 6.5. Surface Cleaned by Shot Blasting Showing Remaining Exterior Dirt

Figure 6.6. Corrosion Removed From Sand Blasting with the 60 Mesh

Figure 6.7. Paint Removed from Sand Blasting

Figure 6.8. Effects of Shot Blasting on Pavement

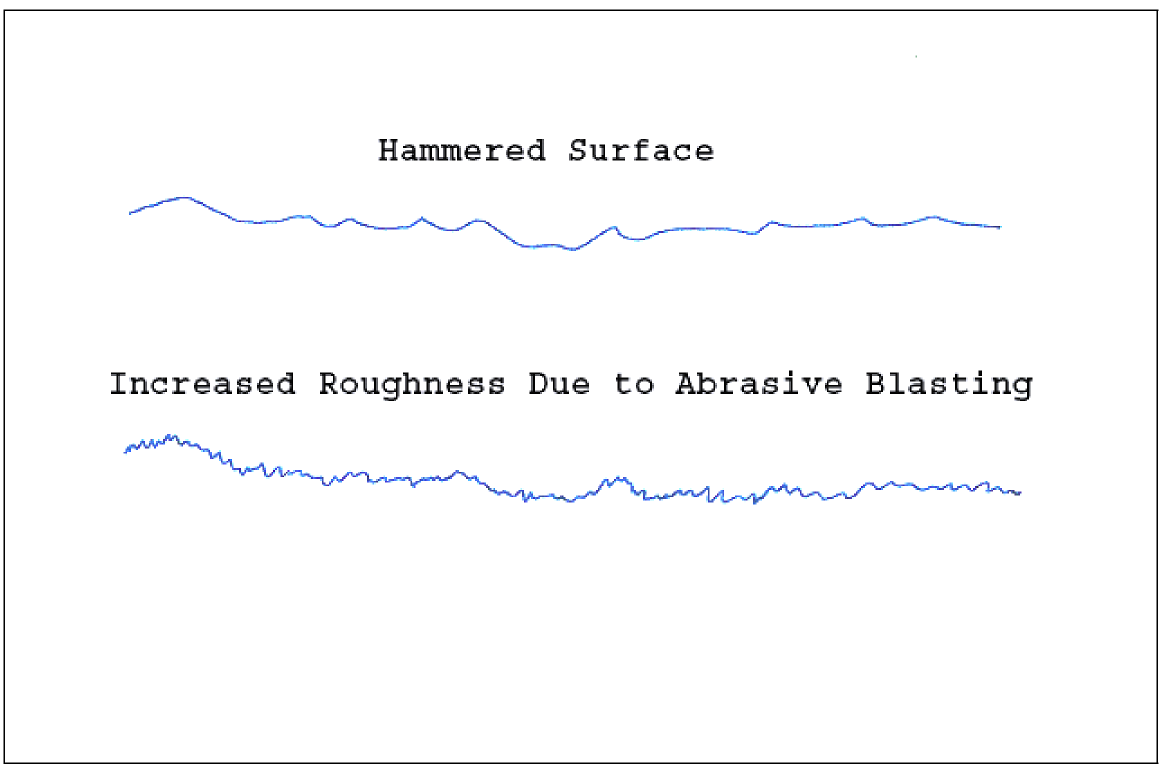


Figure 6.9. Observed Effects of Abrasive Blasting on Hammered Surfaces

Figure 7.1. Example of Failure within Repair Material

Figure 7.2. Example of Failure within Repair/Interface

Figure 7.3. Example of Interfacial Failure

Figure 7.4. Example of Substrate/Interface Failure

Figure 7.5. Example of Failure Deep within Substrate

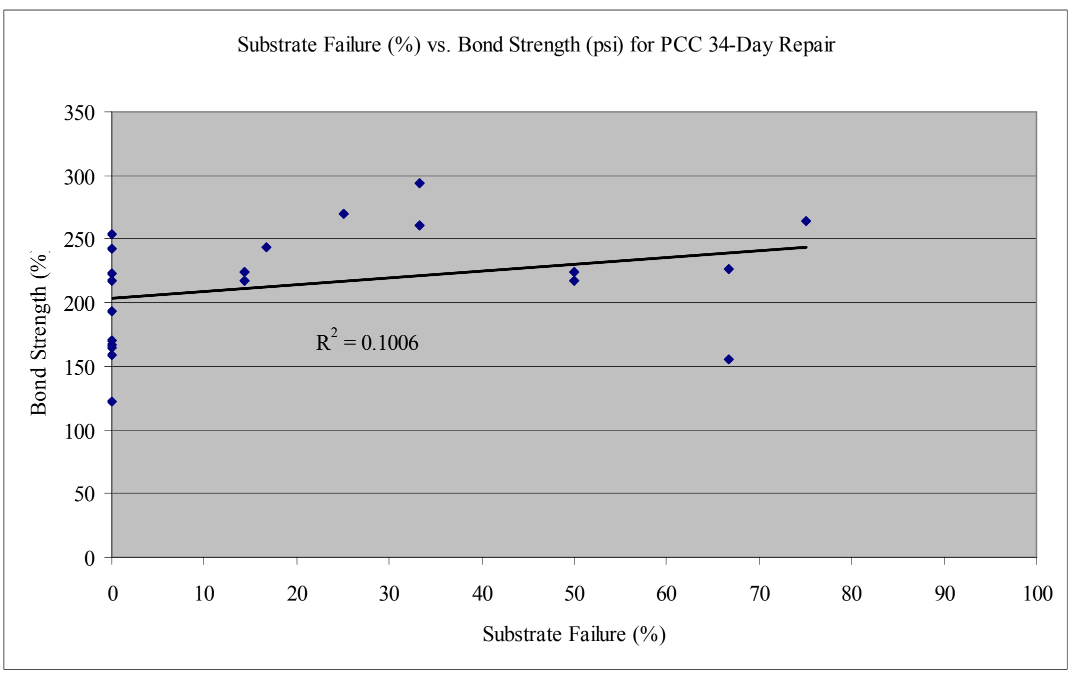


Figure 7.6. Substrate Failure Rates vs. Bond Strength for PCC

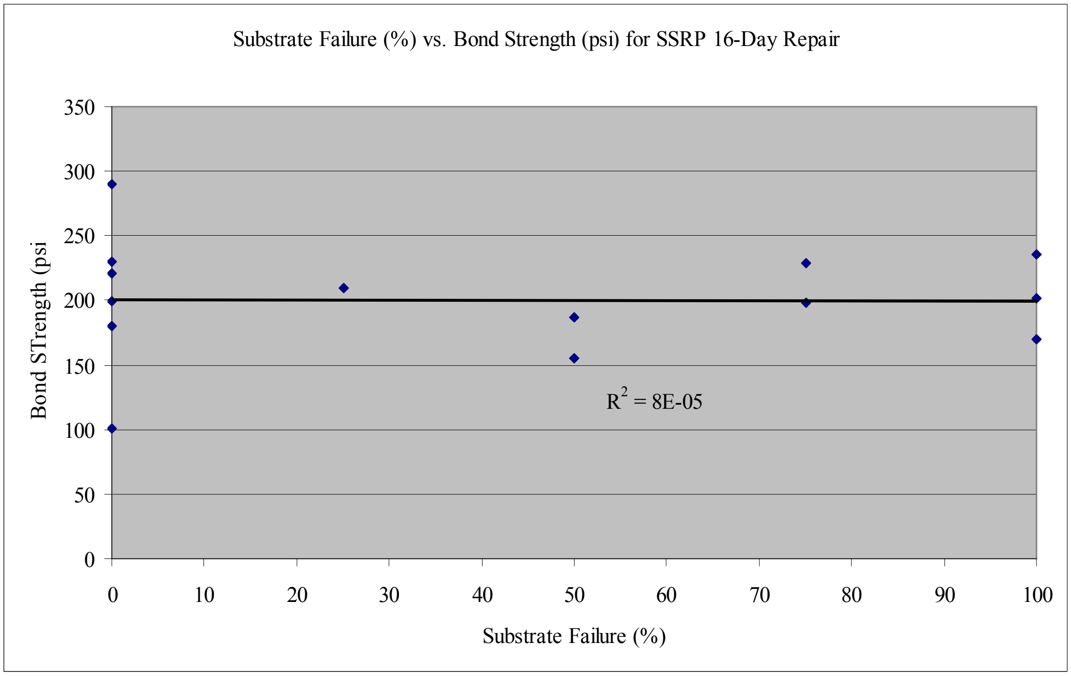


Figure 7.7. Substrate Failure Rates vs. Bond Strength for SSRP 16-Day

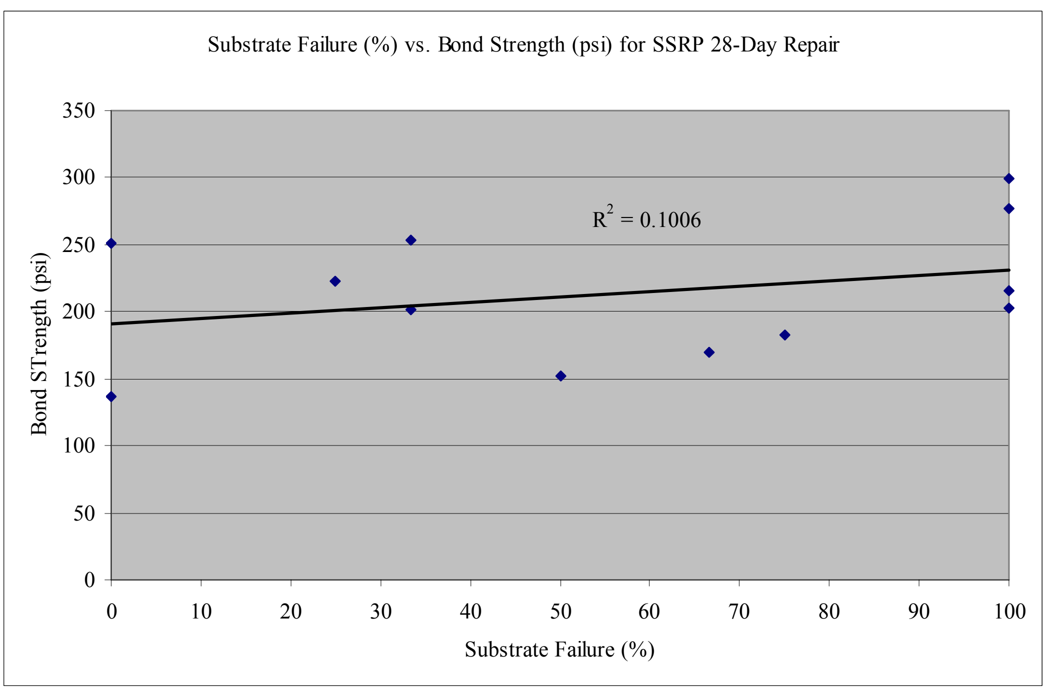


Figure 7.8. Substrate Failure Rates vs. Bond Strength for SSRP 28-Day

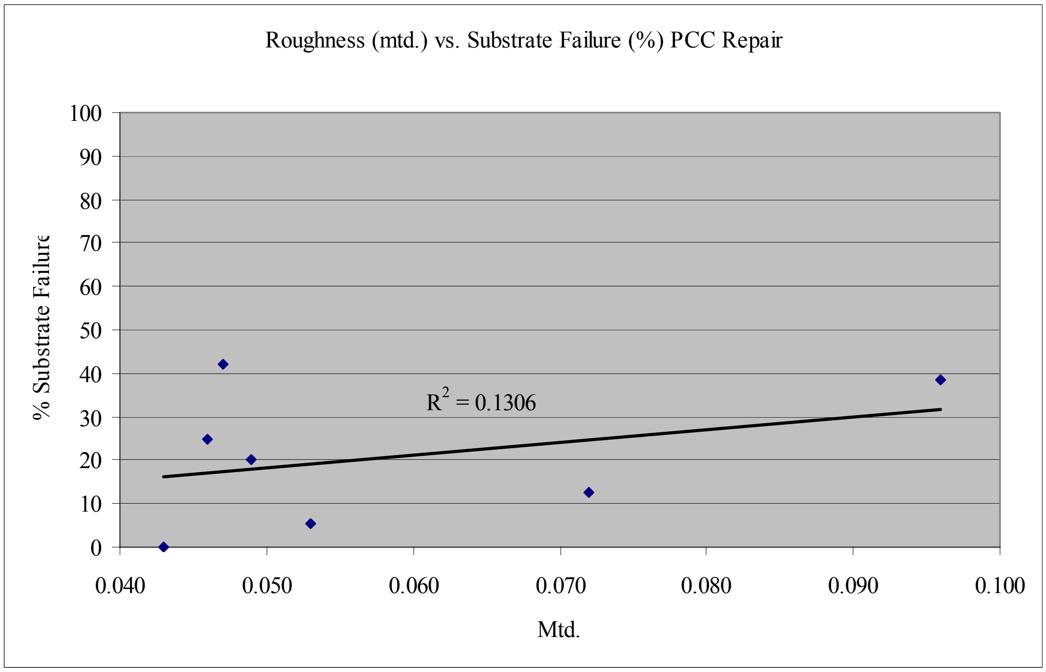


Figure 7.9. Roughness vs. Substrate Failure Rate for PCC Repair

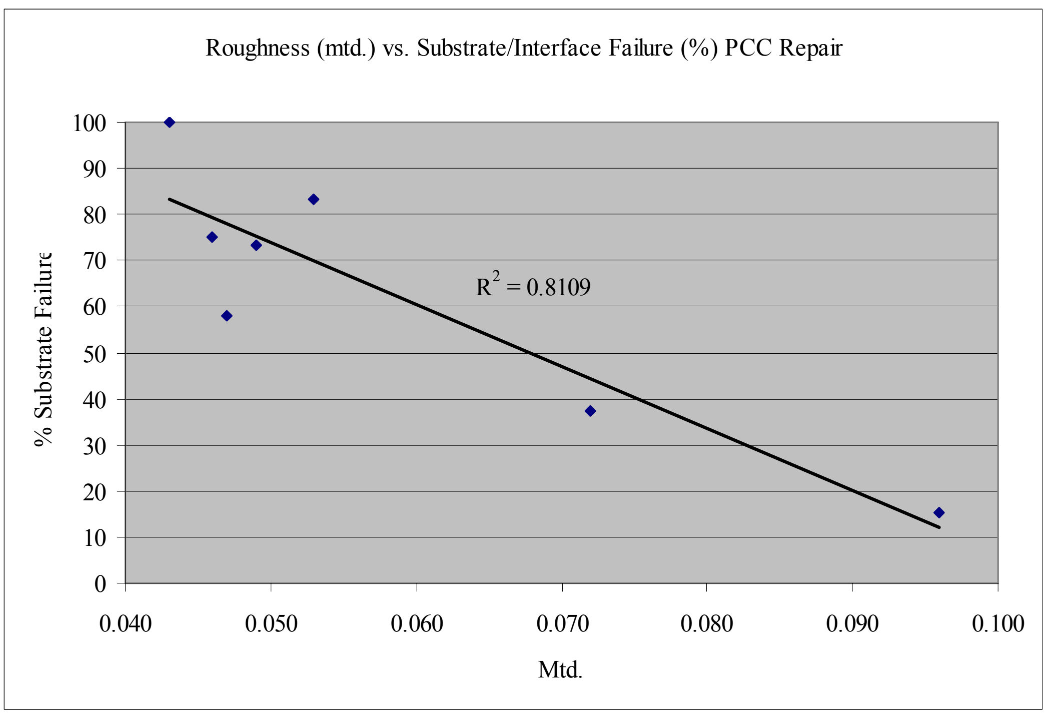


Figure 7.10. Roughness vs. Substrate/Interface Failure Rate for PCC Repair

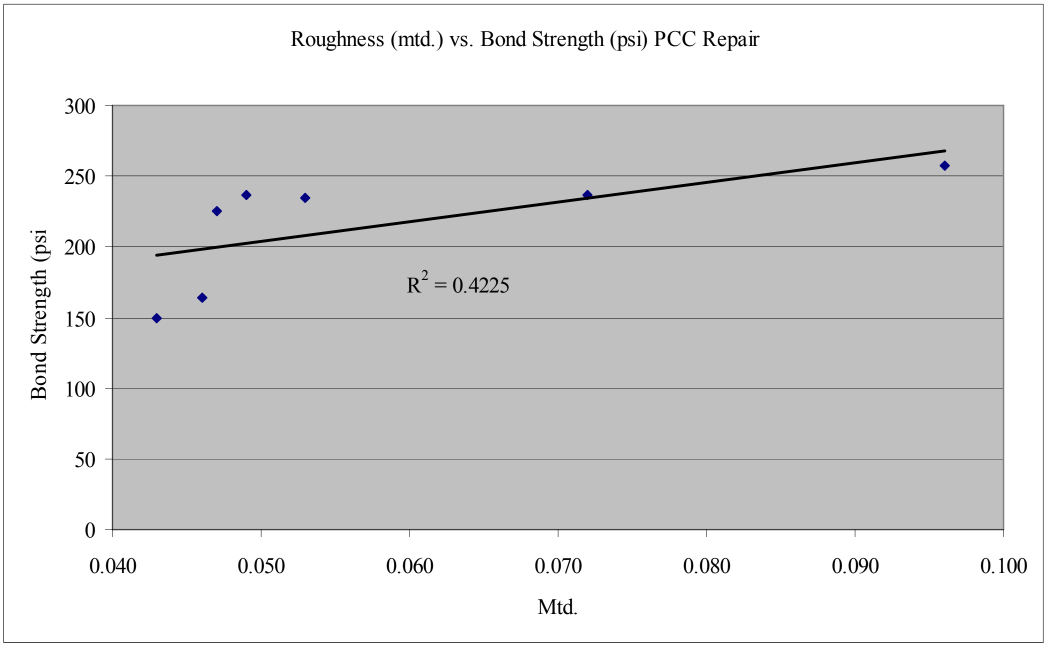


Figure 7.11. Roughness vs. Bond Strength for PCC Repair

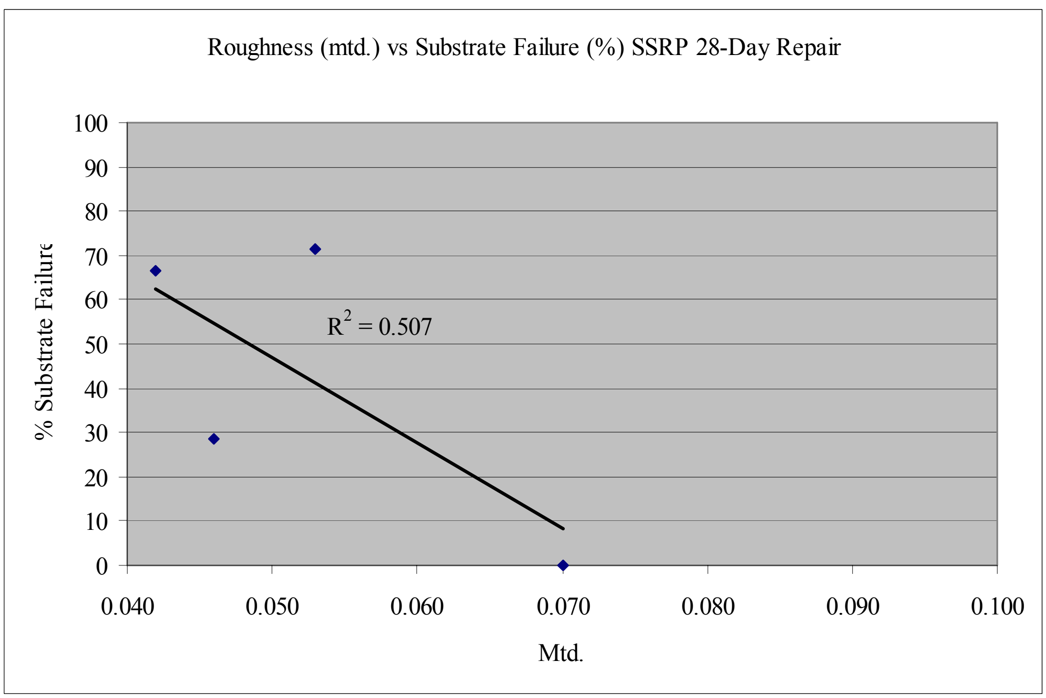


Figure 7.12. Roughness vs. Substrate Failure Rate for SSRP 28-Day

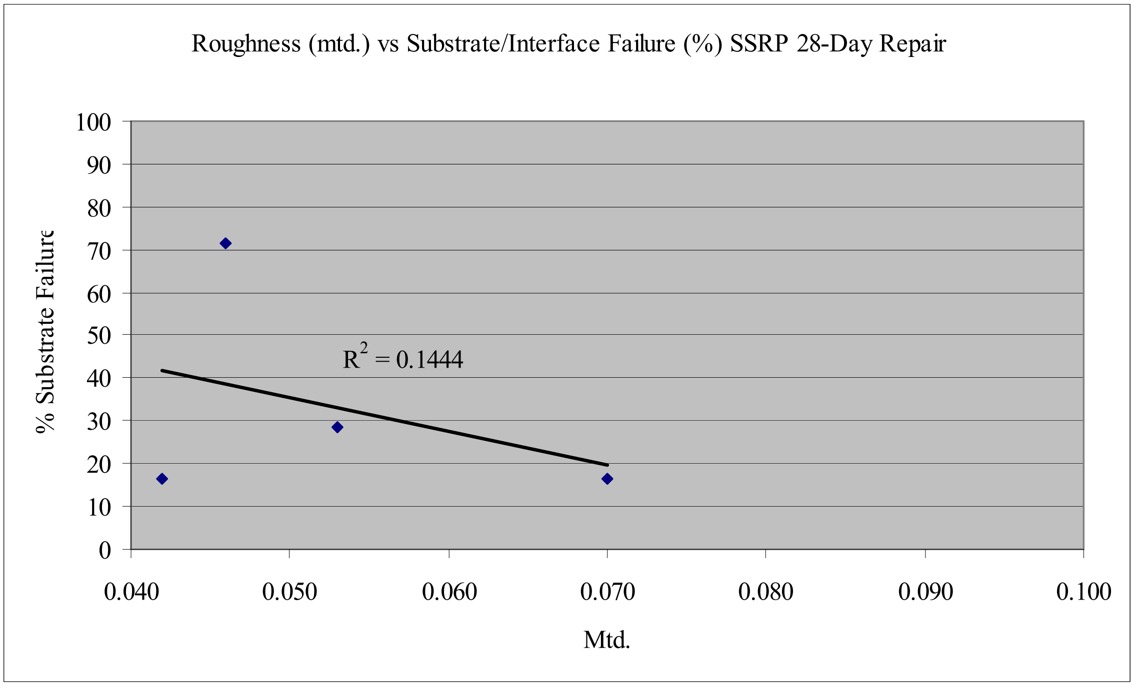


Figure 7.13. Roughness vs. Substrate/Interface Failure Rate for SSRP 28-Day

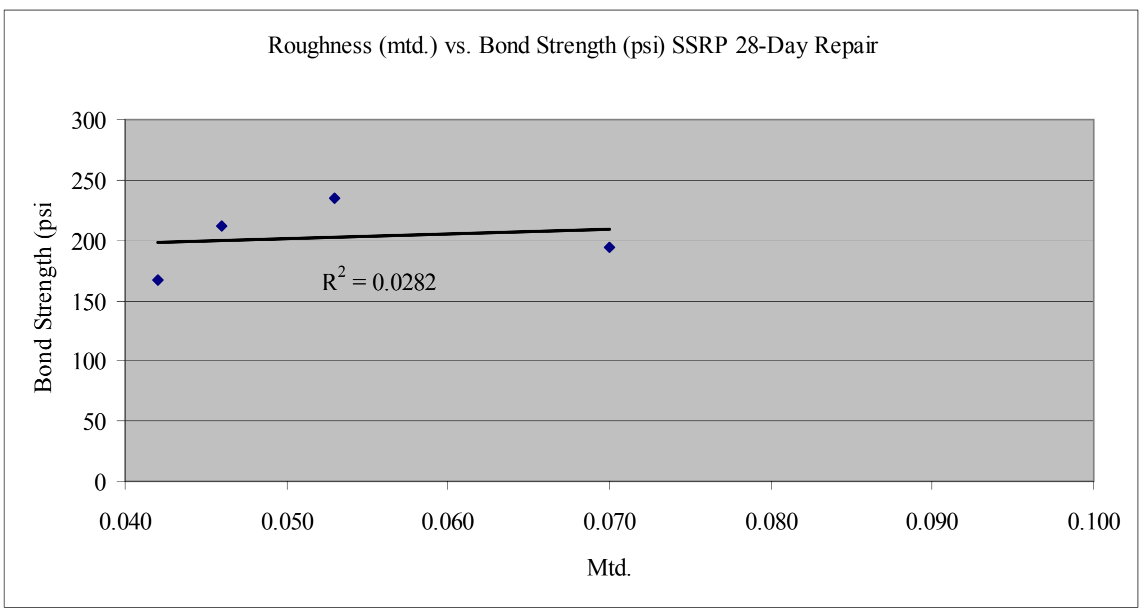


Figure 7.14. Roughness vs. Bond Strength for SSRP 28-Day

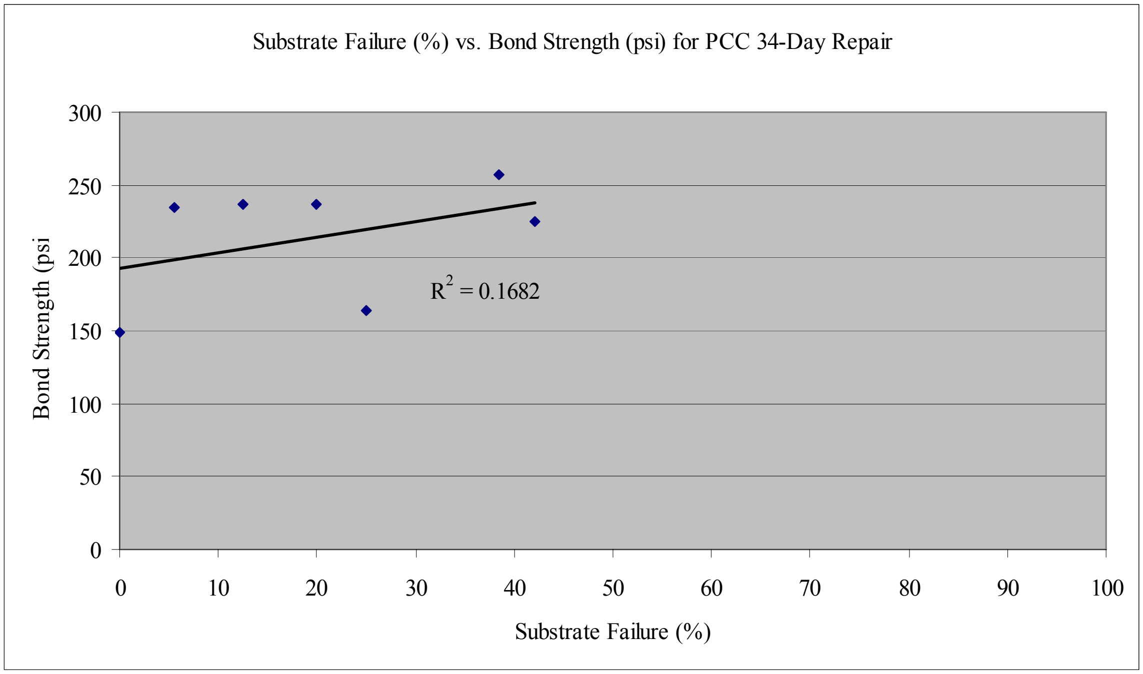


Figure 7.15. Surface Conditioning Method Substrate Failure Rate vs. Bond Strength for PCC

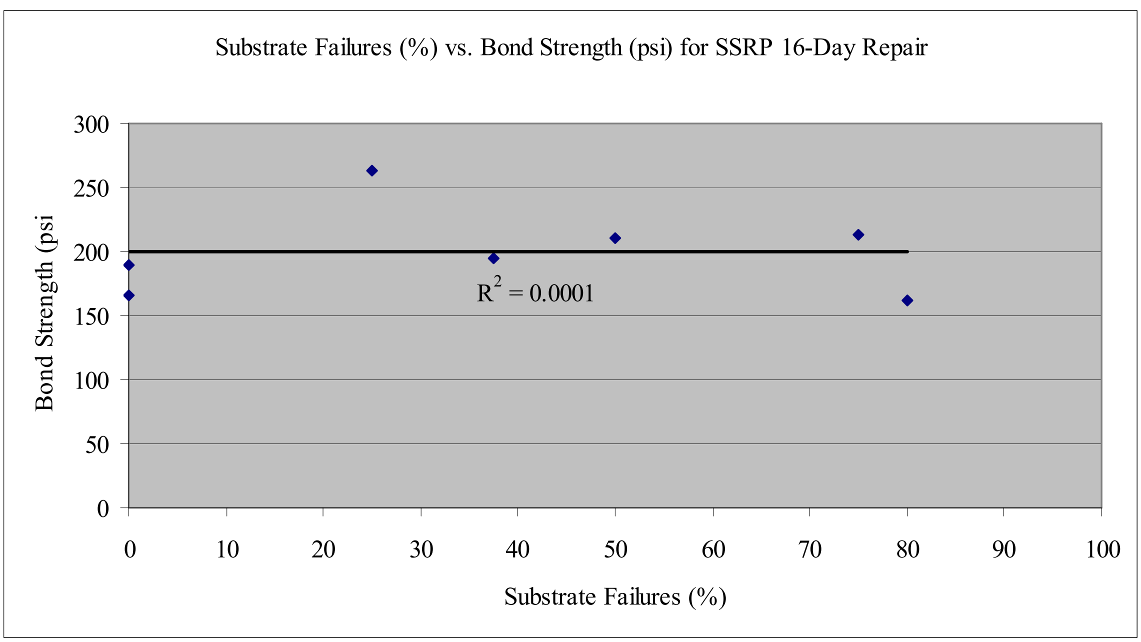


Figure 7.16. Surface Conditioning Method Substrate Failure Rate vs. Bond Strength for SSRP 16-Day

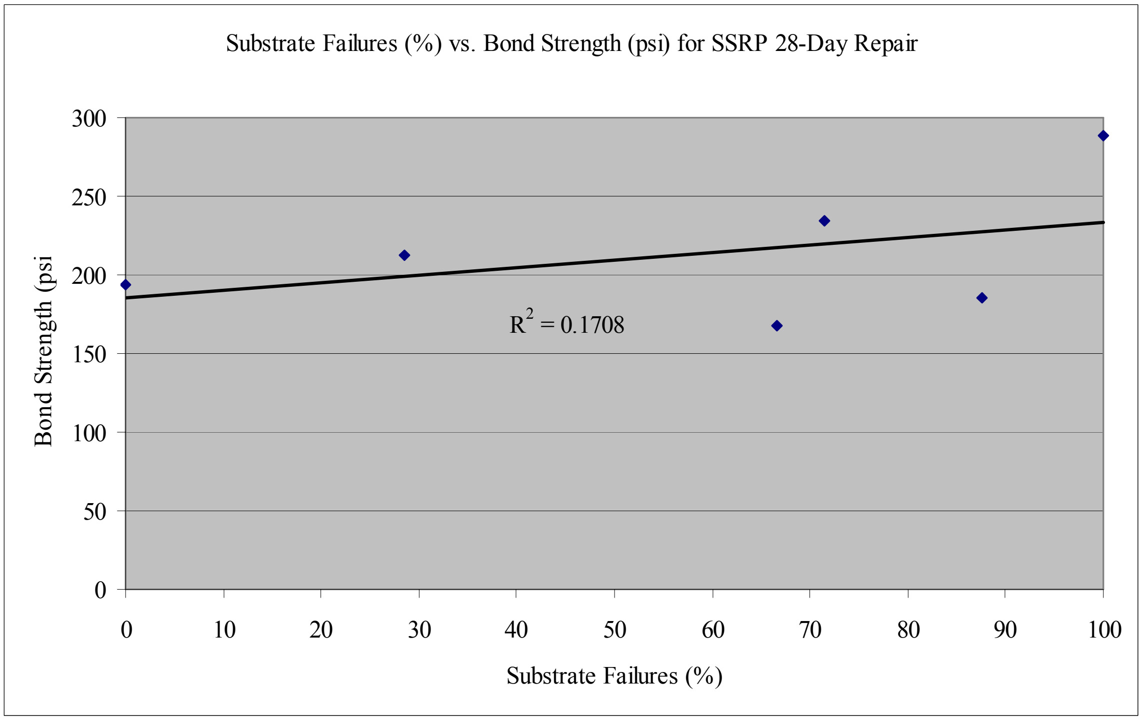


Figure 7.17. Surface Conditioning Method Substrate Failure Rate vs. Bond Strength for SSRP 28-Day

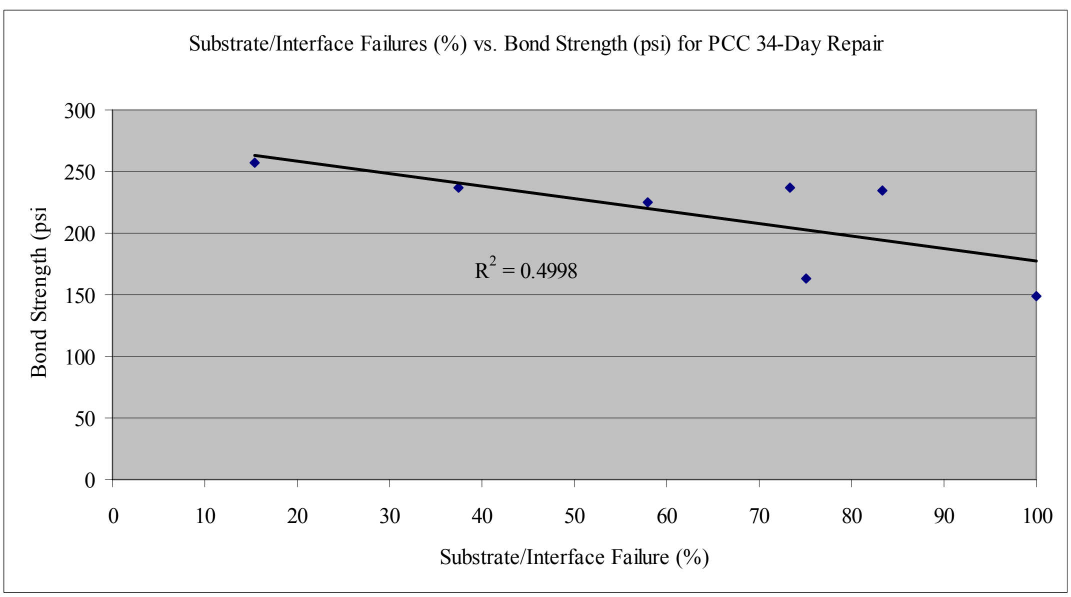


Figure 7.18. Surface Conditioning Method Substrate/Interface Failure Rate vs. Bond Strength for PCC

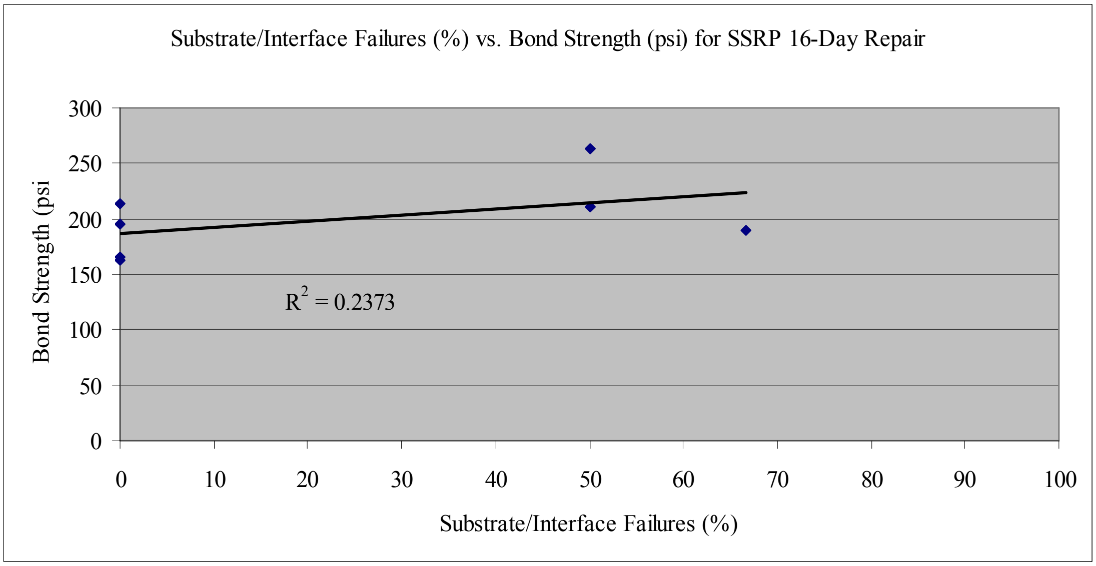


Figure 7.19. Surface Conditioning Method Substrate/Interface Failure Rate vs. Bond Strength for SSRP 16-Day

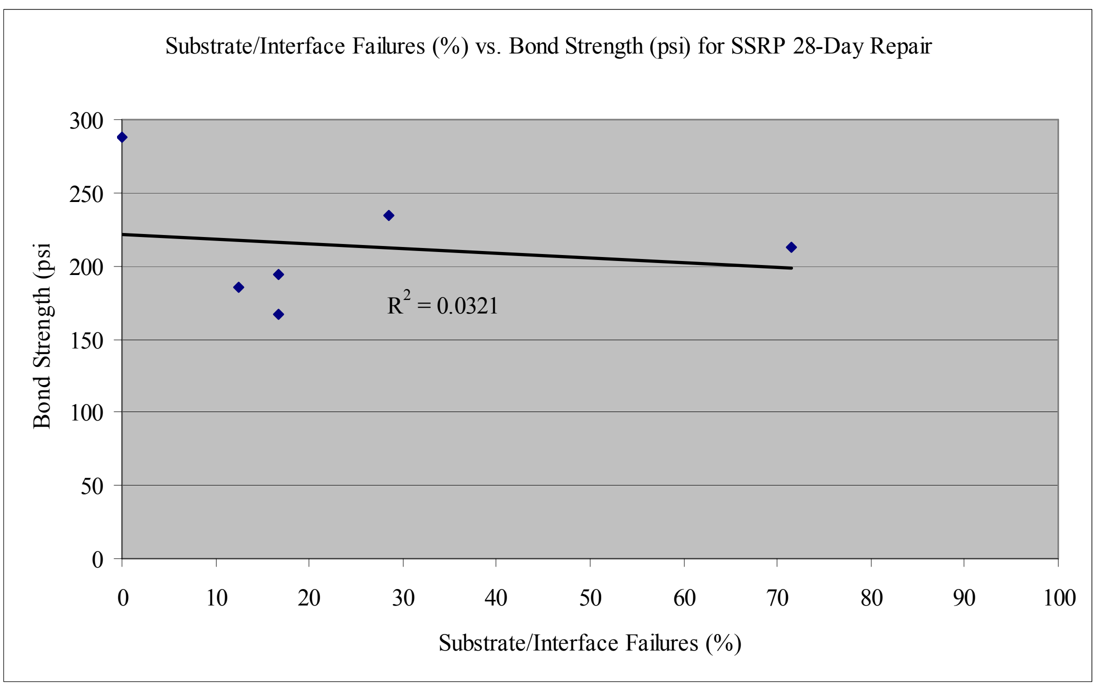


Figure 7.20. Surface Conditioning Method Substrate/Interface Failure Rate vs. Bond Strength for SSRP 28-Day

Figure 7.21. Voids Present in Typical Interfacial Failure Core for PCC Results

Figure 8.1. Epoxy Layer Identification within Tested Core

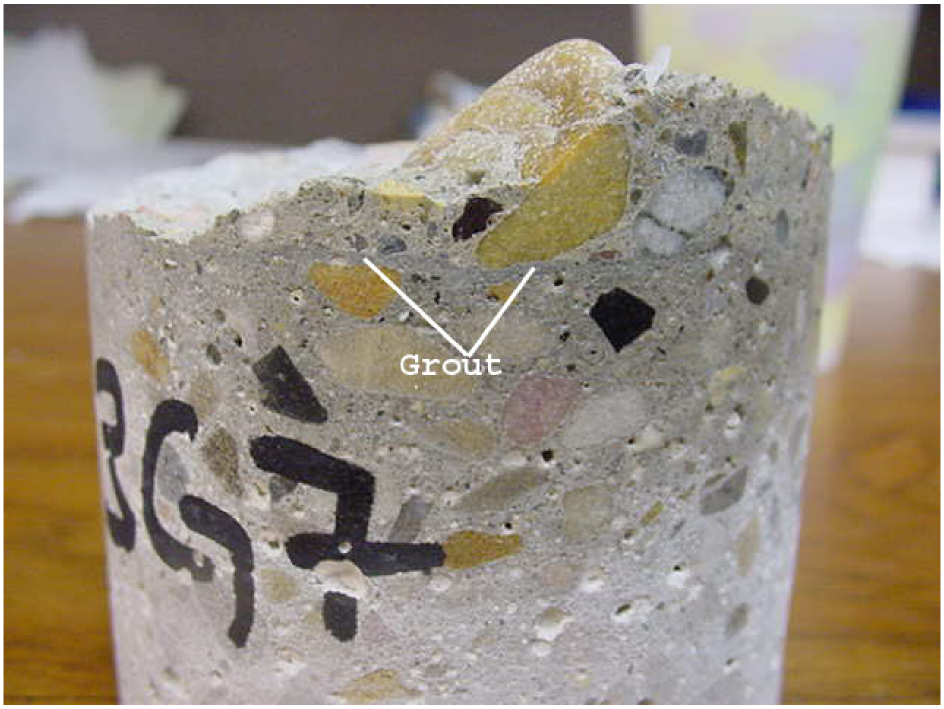


Figure 8.2. Grout Layer Identification within Tested Core

Appendix A

HydroChem
INDUSTRIAL SERVICES, INC.

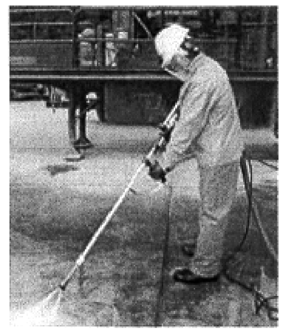
HYDROBLASTING/UHP

900 Georgia Avenue ■ Deer Park, Texas 77536 ■ (713) 393-5600 ■ (800) WE-CLEAN ■ Fax: (713) 393-5950 ■ www.HydroChem.com

Gyro Gun

. . . can quickly be adapted to almost any job situation . . .

Benefits



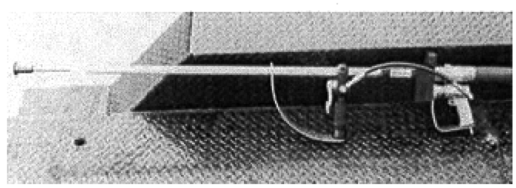
- **Economical**
- **Efficient**
- **Safe**
- **Versatile**

Developed by HydroChem's engineering group, the Gyro Gun hydroblasting tool makes cleaning far easier and more efficient. Because it is so versatile, the Gyro Gun can be used in a variety of applications, from cleaning slabs and walls to removing plastics and rubbers from vessels. It can also be used with a variety of pumps operating at pressures from 10,000 psi to 40,000 psi and flows up to 20 gpm. By simply changing jewel tip sizes and hose fittings, the Gyro Gun can quickly be adapted to almost any job situation.

The rotating nozzle head provides more thorough cleaning action and cleans a larger area - up to 2-1/2 inches - than conventional nonrotating equipment.

Safety was a primary concern in the design of the Gyro Gun. Its 66-inch length meets company minimum guidelines, and the double air trigger system reduces the risk of high pressure water being activated unintentionally.

You can depend on the experienced team at HydroChem Industrial Services and our Gyro Gun to clean unwanted deposits from many different surfaces. Call your HydroChem representative to learn how we can successfully complete any cleaning job, while saving you money and time.



900 Georgia Avenue ■ Deer Park, Texas 77536 ■ (713) 393-5600 ■ (800) WE-CLEAN ■ Fax: (713) 393-5950 ■ www.HydroChem.com

RUBY GARNET

TARGET PRODUCTS LTD

PRODUCT

Ruby Garnet is a naturally occurring almandite garnet, the hardest of all known garnet types, and is mined from alluvial deposits in Montana's Ruby Valley. All grades have a Moh's hardness of 7.5 to 8, with a specific gravity of 3.8 to 4.2. Ruby Garnet is available in size grades to meet requirements for any project.

Ruby Garnet is distributed in Western Canada exclusively by Target Products Ltd.

USES AND ADVANTAGES

- Ruby Garnet is available in all of the sizes required by industry today for dry blasting in shipyards, pulp and paper mills, and fabrication shops, waterjet cutting, filtration, and polymer mortars or surface coatings.
- The angular to sub-angular particle size is proven to be very fast cutting, and provides a super clean surface for protective coating applications.
- Ruby Garnet is chemically inert, with less than 1% free silica and no heavy metals.
- Ruby Garnet is recoverable and reusable.
- Garnet is classified in Fisheries and Oceans Canada Report No. 1692 of January 1991 as:
  (a) having moderate to low toxicity to fish, i.e. 96-h $LC_{50} \geq 100$ mg/L. (Test value was >70000 mg/L.).
  (b) not known to be persistent and not likely to accumulate in animal tissues.

TYPICAL APPLICATION DATA

R16	Coarse abrasive blasting material for heavy rust and mill scale. Slip-resistant aggregate for traffic grade coatings.
R36	Light paint and rust removal, wood signs, non-ferrous metal, high-pressure waterblasting.
R30/40	Light rust and mill scale, waterblasting, non-ferrous metals, smooth finish, and filtration.
R50	Jet cutting, polishing, non ferrous, honing, deburring.
R60	Metals and alloys, wood, plastic, fine honing and deburring, jet cutting.
R60/80	Polishing, deburring, fine honing, fine stripping, jet cutting, non ferrous metals, plastics, woods, alloys.
R80	Water-jet cutting
R100, R120 R150	Fine polishing, deburring, fine stripping

RUBY GARNET

PHYSICAL PROPERTIES

Colour	Purple/Burgundy
Grain Shape	Sub-angular to angular
Hardness, Moh	7.5 - 8
Bulk Density	120 - 160 lb/ft^3 (1922 - 2563 kg/m^3), depending on gradation
Specific Gravity	3.8 - 4.2
Silica Content	<0.1% weight

PACKAGING

Ruby Garnet is available in 22.7 kg (50 lb) and 43.4 kg (100 lb) paper bags, bulk bags, and in bulk by truck or rail.

SAFETY

Target Ruby Garnet Abrasive Blasting Material does not contain any ingredients which require classification under WHMIS regulations. Because of the hazardous nature of abrasive blast cleaning operations and the toxicity of the dusts that can be created when removing certain coatings, all appropriate safety precautions must be followed when using Target Ruby Garnet Abrasive Blasting Material or any other abrasive. Consult your local Industrial Health & Safety Regulations, NIOSH or other requirements for guidance on the required safety procedures and equipment.

TYPICAL CHEMICAL ANALYSIS

COMPOSITION	R 120	R 30/40
SiO_2	35.60%	35.80%
TiO_2	0.48%	0.51%
Al_2O_3	15.60%	15.50%
FeO	21.30%	20.70%
MnO	0.78%	0.78%
MgO	5.68%	5.67%
CaO	5.91%	5.95%

TARGET PRODUCTS LTD

Product performance is affected by many factors, including storage, method and conditions of application and use. User testing is ESSENTIAL to determine suitability of product for intended method of application and use. Target's SOLE WARRANTY is that the product has been manufactured to specifications. No oral or written information or advice shall increase this warranty or create new warranties. Target's SOLE LIABILITY is to replace product proved defective. In no event shall Target be liable for any consequential, indirect or other damages whether arising from negligence or otherwise.

RUBY GARNET

RUBY GARNET ABRASIVE SPECIFICATIONS – Percent Passing

Coarse Grades

Sieve Size		R8	R8/12	R8/16	R16	R25	R36	R30/40
US #	mm							
4	4.75	100						
6	3.35	80-95	100	100				
8	2.36	10-35	80-98	85-100				
10	2.00	0-5	35-75	70-95	100	100		
12	1.70		20-50	40-75	90-100	90-100		
14	1.40		0-10	20-50	60-85	75-90		
16	1.18		0-3	5-25	20-50	30-55	100	
18	1.00			0-15	5-25	20-40	80-95	
20	0.850			0-5	0-5	8-25	35-75	100
30	0.600					0-7	2-16	70-95
40	0.425					0-2	0-3	8-30
50	0.300							0-5

Fine Grades

Sieve Size		R50	R60	R60/80	R80	R100	R120	R150
US #	mm							
20	0.850	100						
30	0.600	75-95	100	100	100	100		
40	0.425	25-50	80-95	90-98	98-100	98-100		
50	0.300	10-30	10-45	45-75	70-80	94-100		
60	0.250	0-12	0-12	25-50	30-50	65-85	100	
70	0.212	0-2	0-2	10-30	8-25	45-70	98-100	100
80	0.180			2-13	0-10	25-50	80-90	98-100
100	0.150			0-3	0-5	10-30	40-70	90-100
120	0.125				0-2	0-12	15-30	60-85
140	0.106					0-3	0-10	25-50
170	0.090						0-3	10-25
200	0.075							0-5

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RUBY GARNET

RUBY GARNET ABRASIVE SPECIFICATIONS - Percent Retained

Coarse Grades

Sieve Size		R8	R8/12	R8/16	R16	R25	R36	R30/40
US #	mm							
6	3.35	5-15						
8	2.36	30-70	2-15	0-15				
10	2.00	5-30	15-35	5-30				
12	1.70	0-5	20-40	20-50	2-10	2-10		
14	1.40		20-40	15-40	15-35	10-25		
16	1.18		0-10	15-45	20-50	20-50		
18	1.00		0-3	2-20	10-40	15-35	5-20	
20	0.850			0-10	5-20	10-30	15-35	
30	0.600			0-5	0-5	10-25	30-70	5-30
40	0.425					0-5	0-15	20-60
50	0.300					0-2	0-3	5-30
60	0.250							0-5

Fine Grades

US SIEVE SIZE		R50	R60	R60/80	R80	R100	R120	R150
U.S #	mm							
30	0.600	5-25						
40	0.425	30-70	5-20	2-10	0-2	0-2		
50	0.300	15-40	40-70	20-60	20-30	0-5		
60	0.250	5-20	5-40	10-30	15-25	10-40		
70	0.212	0-10	0-10	10-30	15-25	15-40	0-2	
80	0.180	0-2	0-2	5-25	5-15	15-40	10-20	0-2
100	0.150			0-10	0-5	15-35	25-35	0-10
120	0.125			0-3	0-3	10-20	25-35	10-40
140	0.106				0-2	0-10	10-20	10-40
170	0.090					0-3	0-7	5-30
200	0.075						0-3	5-20
230	0.063							0-5

The sieve analysis given in the above tables are typical values. Actual values could change from time to time.

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STEEL SHOT STEEL GRIT AMAMIX FERROBLAST AMACAST ERVIN-NIKRO AMACUT EXCALIBUR BALLAST PEENING SHOT FERROCUT

steel shot

Data Sheet

The following are condensations of the Society of Automotive Engineers and Steel Founders' Society of America specifications for cast steel abrosives and include all of the essential features of both specifications. For greater details, request copies of these complete specifications from your Amasteel Representative.

SOCIETY OF AUTOMOTIVE ENGINEERS J827 Cast Steel Shot

Chemical Analysis

Carbon	0.85-1.2%
Manganese	
S-70 - S-110	0.35-1.2%
S-170	0.50- 1.2%
S-230 and Larger	0.60 - 1.20%
Silicon	0.40% minimum
Sulfur	0.05% maximum
Phosphorous	0.05% maximum

Microstructure

The microstructure of cast steel shot shall be uniform martensite tempered to a degree consistent with the hardness range, with fine well distributed carbides, if any.

Density

The density of cast steel shot shall be not less than 7 gm/cc.

General Appearance

The cast steel shot shall be as nearly spherical as commercially possible and no more than 20% of the shot particles shall have objectionable defects.

Hardness

Ninety percent of the hardness checks performed on a representative sample shall fall within the range of 390-510 VPN hardness number (40-50 HRC). (The hardness may be determined by any of the various methods applicable to small sections such as Tukon Tester with VPN indenter, at loads determined to provide a reliable conversion to Rockwell C.) (This is Ervin AMASTEEL 'S' hardness designed for shot and grit

Mechanical Tests

Several designs of shot testing machines are available commercially for application to routine procedures See SAE J445 for methods of checking uniformity of shipments of shot or grit to determine relative fatigue life of different types of shot or grit.

Ervin AMASTEEL Special Hardness

L hardness - 90% minimum (55-60 HRC) 630 - 730 VPN
H hardness - 90% minimum (60 HRC minimum) 700 VPN minimum. AMASTEEL is also available in other

hardness ranges. For these requirements, the hardness of 90 % of the representative sample shall be within a 100 point VPN range (6 point HRC).

STEEL FOUNDERS'SOCIETY OF AMERICA 20-66 Standard Specification for Cast Steel Abrasives

Microstructure

The microstructure of the abrasive shall consist of martensite tempered to a degree consistent with the hardness range The presence of free ferrite or free graphite is unsatisfactory.

Voids

No more than 10% of cast steel abrasive particles shall contain voids as determined at 10X magnification A void must be greater than 10% of the area of the abrasive particle to be considered harmful.

Shrinkage

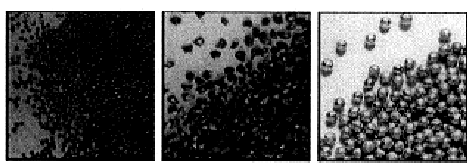
No more than 10% of cast steel abrasive particles shall contain shrinkage as deterwined at 10X magnification A shrinkage area must be greater than 40% of the area of the abrasive particle to be considered harmful.

Cracks

No more than 15% of cast steel shot particles, and no more than 40% of cast steel grit particles, shall have cracks as determined at 10X magnification. A crack is a linear discontinuity whose length is greater than 3 times its width and greater than 20% of the diameter

Particle Shape of Shot

When examined at 4X magnification, no more than 5% of the shot particles will have a length that is in excess of twice the cross section



Information given in this data sheet is intended for guidance only.

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